# Fire History of *Pseudotsuga menziesii* and *Abies grandis* Stands in the Blue Mountains of Oregon and Washington

by

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Abstract

A Fire History Survey in Selected *Pseudotsuga menziesii* and *Abies grandis* Stands in the Blue Mountains of Oregon and Washington

by Kathleen Ryoko Maruoka

Chairman of Supervisory Committee: Professor James K. Agee
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Fifteen sites in the Blue Mountains of Oregon and Washington were sampled to survey fire frequency in stands ranging from *Pseudotsuga menziesii* associations to dry *Abies grandis* associations. Current stand structure at 80% of the sites consists of an overstory dominated by ponderosa pine, with Douglas-fir and grand fir the understory dominants. Pulses of establishment of Douglas-fir and grand fir occurred after the last recorded fire at 53% of the sites, while establishment pulses occurred amidst years of recorded fires at 47% of the sites. Patchiness in fire severity and fire spread, variable regeneration patterns, and sampling design may have influenced the interpretation of current stand structure in the context of fire. Fire scar analyses reveal high variability in fire return intervals. Mean fire return intervals at each site range from 9.9 years to 49.0 years. Individual fire return intervals range from 2 years to 119 years, but may be highly subject to sampling limitations. Fire frequency variability could not be linked between sites to physical or geographic gradients.

## Acknowledgments

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# Introduction

Fire is a powerful physical phenomenon which affects forests on several levels. It influences species composition, forest structure, and nutrient availability on a stand level, vegetation patterns on a landscape level, and disturbance regimes on an ecosystem level (Habeck and Mutch 1973, Kozlowski and Ahlgren 1974, Hall 1976, Romme 1982, White and Pickett 1985, Kauffman 1990, Oliver and Larson 1990). Because it is a physical phenomenon, fire might be perceived as an exogenous force imposed upon a landscape. Indeed, most natural ignitions in the Pacific Northwest are a result of lightning strikes (Morris 1934, Barrows et al. 1977, Pickford et al. 1980), and aside from topographic influences, the landscape has little effect on the frequency of potential ignitions. However, fire ignition and spread is greatly influenced by the physical and floristic characteristics of the landscape (Morris 1934, Romme 1982, Kauffman 1990, Martin 1990, Agee 1993). These interactions link the exogenous nature of fire with the landscape and emphasize that fire is an integral ecosystem process, rather than merely a physical phenomenon which occurs in a forest environment.

Various natural disturbances act in concert to perpetuate cycles of renewal in forests (Gara et al. 1985, Pickett and White 1985, Anderson et al. 1987, Knight 1987, Sprugel 1991, Hadley and Veblen 1993). Fire, insects, pathogens, wind, and other disturbances contribute to landscape and species diversity. Disturbance events affect the occurrence, extent, type, and magnitude of subsequent disturbances even when they occur discretely in time or space. For instance, it has been suggested that fire suppression in the Rocky Mountains and the Blue Mountains, has resulted in larger western spruce budworm (*Choristoneura occidentalis*) outbreaks than previously recorded (McCune 1983, Anderson et al. 1987, Gast et al. 1991). In the absence of fire, shade-tolerant species susceptible to western spruce budworm attacks have established in the understory, and a canopy structure favorable for the spread of western spruce budworm has developed. Because larger outbreaks increase the number of dead and weakened trees, they influence the magnitude of subsequent fire and wind events (Marsden 1983). Geizler et al. (1980) and Gara et al. (1985) documented the interrelationships between insects, fungi, and fire in a southern Oregon climax *Pinus contorta* (lodgepole pine) forest and found that all three played distinct and identifiable roles in stand development.

It is difficult to separate environmental factors, vegetative and fuel characteristics, and disturbance history when describing the various influences on fuel load and consequently, on the presence and effects of fire in a forest. Fire may initiate, perpetuate, limit, or have no effect on other forest disturbances or patterns. Conversely, other forest patterns and disturbances may or may not affect the nature and impacts of fire.

This study provides basic information about fire frequency and frequency variability in selected forests in the Blue Mountains where *Pinus ponderosa* (ponderosa pine) is co-dominant with *Pseudotsuga menziesii* (Douglas-fir) and *Abies grandis* (grand fir) (*Pseudotsuga menziesii* and *Abies grandis* associations, respectively). The influence of fire on current stand structure and composition was also examined. Although reconstructing past events does not necessarily predict the likelihood or impacts of future occurrences, such studies provide a starting point for understanding the forces which have shaped our forests.

The terms "forest type" and "vegetation association" are used throughout this thesis to describe stands or forests. A "forest type" describes a forest based on the current dominant and co-dominant overstory trees at a site (e.g. a forest with ponderosa pine and grand fir in the overstory would be considered a ponderosa pine/grand fir forest). A "vegetation association" is based on the concepts of succession and climax communities (Daubenmire 1966). Vegetation associations do not necessarily describe what is present, but describe the eventual ("climax") species composition of a forest, if that forest were allowed to develop in the absence of any disturbances (e.g. a forest with ponderosa pine and grand fir in the overstory would be considered a grand fir (*Abies grandis*) association). "Vegetation associations" are artificial constructs because most forests do not develop in the absence of disturbance, but nevertheless provide a baseline for comparing different forests.

Because "vegetation association" descriptions often contain information about understory species and site moisture, while "forest type" descriptions focus on overstory tree species, forests may be more specifically described using "vegetation associations" than by using "forest types". I have used "forest types" to describe forests when the overall character of the forests are of interest, and "vegetation associations" when more specific distinctions (such as site moisture levels) between forests are important.

## Background Information

### Fire regimes

A fire regime describes the general characteristics of fire, including severity, intensity, extent, seasonality, and frequency (Agee 1981, Heinselman 1981). Fire regimes are useful as general guidelines in fire history studies because study approach depends on the type of fire evidence, which varies with fire severity, frequency, and extent.

Fire regime classifications may be based on vegetation type since vegetation influences fuel load and, consequently, fire behavior (Davis et al. 1980). However, these classifications are generally only locally applicable because of the variation in vegetation types across larger areas (Agee 1993). Heinselman (1981) classified fire regimes using fire frequency, intensity, and spread characteristics. Six regimes, ranging from no natural fires to frequent, low-severity surface fires, to infrequent, high-severity crown fires were defined. Agee (1993) developed a fire regime classification which incorporated forest types and general fire severity. The resulting classification system was a gradient of fire frequencies and severities imposed upon an ordination of dominant forest types with moisture and temperature as the primary axes. This system emphasized the variability of fire across different forest types and environmental gradients.

Although fire regime classifications cannot adequately describe all wildland fires, they provide a basis for comparing the characteristics of typical fires and conceptualizing the influences of fires in different wildland settings. These comparisons are applicable to forest management strategies such as prescribed burning, fire suppression, and wildlife management.

### Factors influencing fire behavior and effects in forests

Fire severity describes the effects of fire on forest ecosystems (Simard 1991, Agee 1993) and reflects historical fire behavior. Fire intensity, the amount of fuel consumed, and the rate of fire spread contribute to fire severity. These characteristics are influenced by conditions which may change, such as wind or moisture, as well as others which are more stable, such as slope or aspect. Therefore, fire severity is not always uniform in a forest, even within a forest which appears homogeneous in topography or vegetation. Differences in fire severity are reflected in forest structure, species composition, and landscape patterns.

Although reconstructing fire behavior is not an essential component of a fire history study, recognizing the influence of variable fire behavior on forest structure is useful when inferring forest development based on current stand structure and fire history.

Physical environment

Topography and weather influence the behavior and consequently the effects of fire in forests. While the physical landform remains stable as a fire burns, fire behavior may change if a change in topography is encountered. For instance, a slow-moving fire may suddenly increase in the rate of spread and intensity if the slope increases rapidly (Brown and Davis 1973, Martin 1990). Fire events may also have a delayed effect on subsequent land mass movements through loss of vegetation and soil stability (Brown and Davis 1973, Swanson 1981, McNabb and Swanson 1990). Slope and aspect are often used to describe the topographic character of a site. These factors may influence fire behavior directly, as with a change in slope, or indirectly, by affecting vegetation patterns.

Weather patterns and conditions vary on temporal scales from years, to months, to hours, and on spatial scales ranging from hundreds of miles to less than one mile and are the most dynamic components of fire behavior. Regional-scale temperature and moisture conditions can be reconstructed and related to trends in fire occurrences using tree-ring chronologies and fire scar analyses (Fritts 1976). While regional or local droughts lasting several days or more affect general fuel moisture and fire potential (Brown and Davis 1973), much more localized wind patterns are responsible for fire behavior and intensity (Brown and Davis 1973, Martin 1990). These local wind patterns can change instantaneously as a fire burns, and render fire behavior unpredictable. The result of such variable fire behavior is a mosaic of different fire severities within a forest, reflected in the species composition, age distribution, and horizontal and vertical stand structure (Weaver 1959, Heinselman 1981, Peterson and Arbaugh 1986, Pitcher 1987).

Soil types and patterns are also important features of the physical environment because they influence vegetation establishment (Barbour et al. 1987) and consequently, fire behavior. Because organic matter and some nutrients are volatilized at temperatures typically exceeded during a fire, and many nutrients are oxidized or leached out, soil nutrient levels following a fire usually differ from pre-fire levels (DeBell and Ralston 1970, White et al. 1973, Tiedemann 1987). Shifts in available soil nutrient levels, increases or decreases in the soil seed bank, and changes in soil biota influence species and establishment patterns following a fire (Borchers and Perry 1990, McNabb and Cromack 1990). Some of these changes return to pre-fire levels within a year (e.g. potassium levels), while other changes persist for years (e.g. some soil bacteria) (Borchers and Perry 1990, McNabb and Cromack 1990, Agee 1993).

Fuels and vegetation

The fuel available to sustain a fire is a function of the absolute amount of combustible material, the ambient humidity, the amount of preheating during a fire, and the fuel-bed arrangement (Brown and Davis 1973, Martin 1990, Agee 1993). General fire behavior varies between forest types as a result of several influences. Species traits such as bark thickness, canopy morphology, foliage flammability, and life history patterns affect tree survival in fires, as well as fire behavior (Flint 1925, Starker 1934, Hare 1965, Ryan and Reinhardt 1988, Kauffman 1990). For example, the thick bark of a mature ponderosa pine provides more thermal protection from surface fires than the thin bark of a species such as lodgepole pine. As a result, a mature lodgepole pine is more susceptible to mortality than a mature ponderosa pine in a low-intensity surface fire. These differences in mortality affect post-fire fuel loads, and consequently the behavior and effects of subsequent fires.

Fuel continuity is an important component of fuel loading in forests. Horizontal fuel continuity is influenced by tree diversity and species mix, as well as the type and density of vegetation between trees, while vertical fuel continuity is a function of individual tree characteristics and canopy layering (Brown and Davis 1973). Fuel continuity may play a more important role in fire spread and intensity than individual tree characteristics in certain situations. For instance, thick bark may protect a ponderosa pine from low-intensity surface fires, but the same tree may be consumed as readily as lodgepole pine in a high-intensity crown fire burning through a dense forest.

Previous disturbances

Previous disturbances affect a forest directly by increasing or reducing the amount of combustible material, and indirectly by influencing vegetation development (Volland and Dell 1981, Pickett and White 1985, Kauffman 1990). Disturbance type, frequency, seasonality, and severity are important to consider in examining the roles previous disturbances have played in forest development. For instance, infrequent, high-severity windstorms, frequent, low-severity surface fires, and moderate-severity seasonal flooding have different influences on the immediate fuel load, vegetation establishment patterns, and subsequent fuel load potentials (Weaver 1959, Bormann and Likens 1979, Barnes 1985, Streng et al. 1989, Veblen et al. 1989). Previous disturbances may be difficult to detect because of more recent disturbances, or because of similarities to other disturbances. For example, small fires may be obliterated by larger fires, and human-caused fires are virtually indistinguishable from natural fires unless accurate historical records are available.

Fire and stand development

Differences in fire frequency, intensity, and extent influence stand development and structure (Wright and Heinselman 1973). Stand-replacing fires can produce dramatic shifts in species composition, although forest successional stage and history, seed source availability, soil patterns, and previous disturbances also influence regeneration patterns (Brown and Davis 1973, Volland and Dell 1981, Romme 1982, Kauffman 1990). In contrast, low- to moderate-severity surface fires may significantly alter stand structure, but changes occur more gradually than those caused by more severe fires (Oliver and Larson 1990). For example, frequent, low-intensity surface fires in seral and climax ponderosa pine forests have historically maintained an open, grassy understory (Wright 1978). In the absence of fire, fire-intolerant shrub and tree understories have slowly developed (Weaver 1959, Hall 1976, Wischnofske and Anderson 1983).

Species composition and age class distributions were used to infer the behavior of some historical fires in mixed-conifer forests in the Rocky Mountains and Sierra Nevada, California (Loope and Gruell 1973, Arno 1976, Kilgore and Taylor 1979, Antos and Habeck 1981). Evidence suggested that fires were generally low- to moderate-intensity, with occasional high-intensity or crowning behavior. The frequency of these fires maintained low levels of fuel-accumulation, and limited understory regeneration, while the variability of fire intensities maintained a mosaic of age classes and species. Species and age distributions at these and other sites exhibited an increase in establishment of fire-intolerant species concomitant a reduction in fire frequency (Weaver 1959, West 1968, Houston 1973, Dickman 1978, Parsons and DeBenedetti 1979).

The absence of fire has affected fuel loads and fuel continuity in forests in which low- to moderate-severity surface fires were historically frequent. Fuels which would have burned in frequent fires have accumulated on the forest floor, and trees which would not have survived frequent fires have established in the forest understory (Weaver 1959, Hall 1976, Parsons and DeBenedetti 1979, van Wagtendonk 1985). These trees increase the fuel load by contributing litter, and creating vertical fuel ladders which allow surface fires to spread into the overstory tree crowns. Several fire behavior models predict a change in species composition, fuel load, and possibly future fire regimes given historical fire occurrences, and present forest stand structures and fire regimes (Marsden 1983, Kercher and Axelrod 1984, van Wagtendonk 1985, Keane et al. 1990).

Fire suppression and human influences

Fire has long been recognized as an integral and influential component of ecosystems (Habeck and Mutch 1973, Wright 1978). Seral and climax ponderosa pine forests, which have historically burned frequently at low intensities, maintained forests with open understories and low fuel-loadings. These open conditions provided forage and habitat for some wildlife species, and provided natural fuel breaks for low-intensity fires (Wright 1978). Native Americans, foresters, rangeland managers, and property owners have used underburning and "controlled" burning practices to mimic these conditions, or perpetuate desirable species (Brown and Davis 1973, Wright 1978, Biswell 1989). Ironically, despite these and other demonstrable benefits, fire was long perceived as an "evil destroyer" of forests (Brown and Davis 1973, Wright and Heinselman 1973, Pyne 1982).

The U.S. Forest Service focused on developing federal fire protection programs during the early 1900's (Pyne 1982). The introductory remarks to a 1915 U.S. Forest Service publication (Graves 1915) exemplified the importance which was placed on fire protection:

> "Fire protection is of first importance in National Forest management. No other work must be allowed to crowd it out. Even the construction of permanent improvements, which is so closely related to the fire problem, must take second place."

Fire suppression efforts did not become effective on a large scale until air-attacks were utilized after World War II. Prior to World War II, the primary attack methods were hand crews and pumper trucks (Pyne 1982). Communication, transportation, and technological advances have greatly enhanced fire suppression operations in the past 50 years. However, despite a strong arsenal of control techniques and materials, seemingly unstoppable conflagrations rage in forested regions of the United States every year.

Successful fire suppression efforts are often credited with causing "unnatural" or "unhealthy" changes in forests with historically frequent fires, although few provide adequate historic documentation for the effectiveness of fire suppression (Reynolds 1959, Wellner 1970, Heinselman 1973). While the studies and models in the previous section show that changes in forest structure have occurred with a decrease in fire frequency, describing the changes as "unnatural" assumes that a previous condition was more "natural". This assumption relies on historical evidence and inferences confounded by other factors, such as climate, often not considered when a forest or forest process is described as "unnatural".

Data collected in this and other studies in mixed-conifer forests in the Blue Mountains document trees which established over 300 years ago (Hall 1976, Bork 1985). The oldest trees in these forests may reflect an assemblage of environmental conditions, including climate, seed sources, and disturbance processes, which are different than the present complement of conditions (Brubaker 1988). While microsite conditions are always quite variable and affect stand development on shorter time scales, longer-scale changes such as shifts in species establishment patterns or abundance influenced by climatic changes are equally as important to consider.

Other human influences confound describing stands as "natural" or "unnatural" (Reynolds 1959, Lewis 1980, Shinn 1980, Dorney and Dorney 1989). Except where very detailed records exist, it is impossible to distinguish between human-caused and natural fires based on fire scars. Although this is acknowledged in fire history studies, historic fire frequencies are nevertheless used with current stand structure as measures of what constitutes "natural" or "healthy" forest stands or processes (such as fire frequency). It is possible that a decrease in fire frequency has contributed to changes in forest structure towards conditions (currently defined as "unnatural") which more closely resemble forests which might have developed under less human influence (Reynolds 1959). Livestock grazing, and more recently, selective timber harvesting, also alter seed sources, microsites, and seedling establishment patterns (Wellner 1970, Hall 1976). However, these influences are often difficult to account for because detailed records are usually scarce.

"Forest health" issues in the Blue Mountains

Forests in the Blue Mountains are currently experiencing heavy insect outbreaks which are reducing productivity and increasing fuel loads (Gast et al. 1991). The primary attacking organisms in the Blue Mountains are the western spruce budworm, Douglas-fir tussock moth (*Orgyia pseudotsugata*), mountain pine beetle (*Dendroctonus ponderosae*), western pine beetle (*Dendroctonus brevicomis*), spruce beetle (*Dendroctonus rufipennis*), Douglas-fir beetle (*Dendroctonus pseudotsugae*), fir engraver (*Scolytus ventralis*), and the pine engraver (*Ips pini*) (Gast et al. 1991). The damage by these insects is readily apparent on individual trees, as well as throughout stands and across landscapes. Attack intensity varies, and while some areas remain unaffected, most of the forests have incurred damage (Gast et al. 1991, Wickman 1992). Forest pathogen levels in the Blue Mountains have also increased during the past 100 years (Gast et al. 1991). Among the most common pathogens influencing stands in the Blue Mountains are various root diseases, dwarf mistletoes, and stem decays.

The "forest health problems" in the Blue Mountains have raised the concerns of the U.S. Forest Service. "Forest health" is difficult to define because it is highly subject to different interpretations of resource values. Defining "forest health" has been resolved among managers in the U.S. Forest Service by replacing "forest health" with "desired future conditions" (Gast et al. 1991). Such terminology allows land managers to state and actively seek management techniques to attain specific outcomes. It does not necessitate a complete knowledge of the components and processes which constitute a "healthy forest".

Recent discussions have centered around ways to "restore" the Blue Mountains to highly productive ecosystems (Gast et al. 1991). Productive ecosystems have been defined by Gast et al. (1991) as those in which "...resources (heat, light, water, and chemicals) within the ecosystem [are redistributed] into products utilized internally by the ecosystem or externally by man...[productivity is] related to the capacity of an ecosystem to exist and generate products in perpetuity". Fire has been recognized as a crucial component to any restoration efforts. However, managers are cautious about incorporating fire into management plans without specific knowledge of the role it has played in shaping the diverse forests of the Blue

Mountains (Gast et al. 1991). Historic fire frequency, intensity, extent, and magnitude need to be considered when formulating the role fire will play in future management activities (Parsons 1981).

Fire history studies

Little direct fire history research has been completed in the Blue Mountains. Hall (1976) documented a mean fire return interval (MFRI) of 10 years in a *Pseudotsuga menziesii/Calamagrostis rubescens* association stand in the Blue Mountains. Bork (unpubl. data) recorded the fire history of stands in six drainages in the Elkhorn Mountains, Oregon. The MFRI for individual trees at these sites ranged from 66-200 years in lodgepole pine stands, 57-133 years in a mixed-conifer/*Calamagrostis rubescens* stand, and 50-200 years in an grand fir stand. The MFRI for the overall study area was calculated to be 8 years, based on a compilation of individual tree chronologies. This MFRI is lower than those typically associated with these vegetation types because MFRI decreases as the area considered increases (Kilgore and Taylor 1979, Arno and Petersen 1983, Agee 1993). The variation in MFRI reflects the different environments throughout the Blue Mountains, differences in fuel types, and topographic influences. Fire occurrences have been noted anecdotally in other studies in the Blue Mountains, but the results remain unpublished (F.C. Hall pers. comm.).

Fire history studies in areas with similar climate and vegetation associations provide background information for this study, which focuses on stands where ponderosa pine is seral to Douglas-fir and grand fir. Wischonfske and Anderson (1983) documented fire frequency in the Wenatchee Valley in eastern Washington for the period between 1715 and 1915. The MFRI at each of four *Pseudotsuga menziesii/Calamagrostis rubescens* association sites ranged from 7.1 to 11.1 years, with fire-free intervals from 1 to 33 years. A much smaller sample size at two grand fir sites revealed MFRIs of 33.3 to 100.0 years, with fire-free intervals from 6 to 62 years.

Arno (1980) compiled a fire history for the northern Rocky Mountains which included sites where Douglas-fir and grand fir were co-dominant with ponderosa pine. The MFRIs calculated for the period 1600-1910 in dry grand fir stands in the Bitterroot Mountains in Montana ranged from 15 to 30 years, with maximum fire-free intervals from 35 to 60 years. Limited data also revealed a MFRI of 70 to 250 years for moist grand fir stands. Variation in fire frequency was described by Kilgore and Taylor (1979) for mixed-conifer stands in the Sierra Nevada, California. Fires were more frequent in dry and west-aspect sites (site MFRIs: 8.4-15.5 years; range: 2-26 years) than on sites which were more mesic or east-aspect (site MFRIs: 14.4-17.8 years; range: 4-39 years). Antos and Habeck (1981) reported fire return intervals of 100 to 200 years in moist grand fir forests in the Swan Valley, Montana based on stand ages. However, it is important to note that this estimate reflects the recurrence of stand-replacing fires, and does not include estimates of low-severity surface fires, which were noted to have occurred at intervals of as low as 20 years.

## Study objectives and questions

A complete fire history of the Blue Mountains across all vegetation types and elevations would require considerable time and effort. This study focused on the "mixed conifer" forests in the Blue Mountains, specifically those in which ponderosa pine is co-dominant with Douglas-fir and grand fir. These forests are particularly interesting because fire regimes are not as well characterized as in forests where ponderosa pine is the dominant species, or in areas which experience infrequent, stand-replacing fires. Although the study objective was a survey of the fire history in "mixed conifer" forests in the Blue Mountains, it is important to recognize that the fire frequency data may have limited applicability since the data are at the scale of the stand.

The possible influences which fire has had on stand development can be estimated by combining a record of fire frequency with current stand structure (age and species composition, basal area, stem density, vertical structure). Understanding how fire may have affected stand development contributes to our basic knowledge of forest development in the mixed-conifer forests in the Blue Mountains, and may be used by managers interested in mimicking the effects of historical fires in the Blue Mountains.

### Objectives

The overall study objective was to characterize the presence of fire in mixed-conifer forests in the Blue Mountains. This broad objective was achieved through three more specific objectives:

1. Document fire occurrences at each site based on fire scar samples.
2. Characterize each stand in terms of tree species and age distributions.
3. Infer the influence of fire on stand structure and composition.

### Study questions

As the data were processed and analyzed, additional questions arose:

1. Are there differences in the MFRIs or sample standard errors between sites?
2. If differences in MFRIs or sample standard errors are detected, do the differences reflect topographic, geographic, or moisture gradients?

## Study Area

The Blue Mountains trend northeast to southwest along an 320-kilometer axis from Pomeroy, Washington to Burns, Oregon (Figure 1). The Blue Mountains and several other mountainous areas comprise the Blue Mountains physiographic province (a geographically contiguous area with similar topographic and vegetative characteristics) (Franklin and Dyrness 1987). Topography varies from gentle terrain to deeply incised river drainages. Elevations in the Blue Mountains range from approximately 750 meters (m) above sea level in several river drainages, to over 2700 m in the southern Blue Mountains.

The climate of the Blue Mountains is considered temperate-continental-cool summer phase (Trewartha 1968), although it is widely variable because of local topography. The Oregon Cascade Range is a major topographic barrier for moisture from the Pacific Ocean (Ruffner and Bair 1984). The Blue Mountains lie within this rainshadow influence, but still receive moisture from Pacific cyclonic storms during the winter months. Thunderstorms during the summer generally approach the Blue Mountains from the south or southwest and often bring light rains (Ruffner and Bair 1984). Average annual precipitation ranges from 40 centimeters (cm) in the southern Blue Mountains to 80 cm in the northern Blue Mountains, with most occurring as snow during the winter (Franklin and Dyrness 1987). Temperatures in Pendleton, OR range from an monthly average of 0.1° C in January to 23.1° C in July, while in the southern Blue Mountains, temperature averages range from -4.1° C in January, to 20.2° C in July (Franklin and Dyrness 1987).

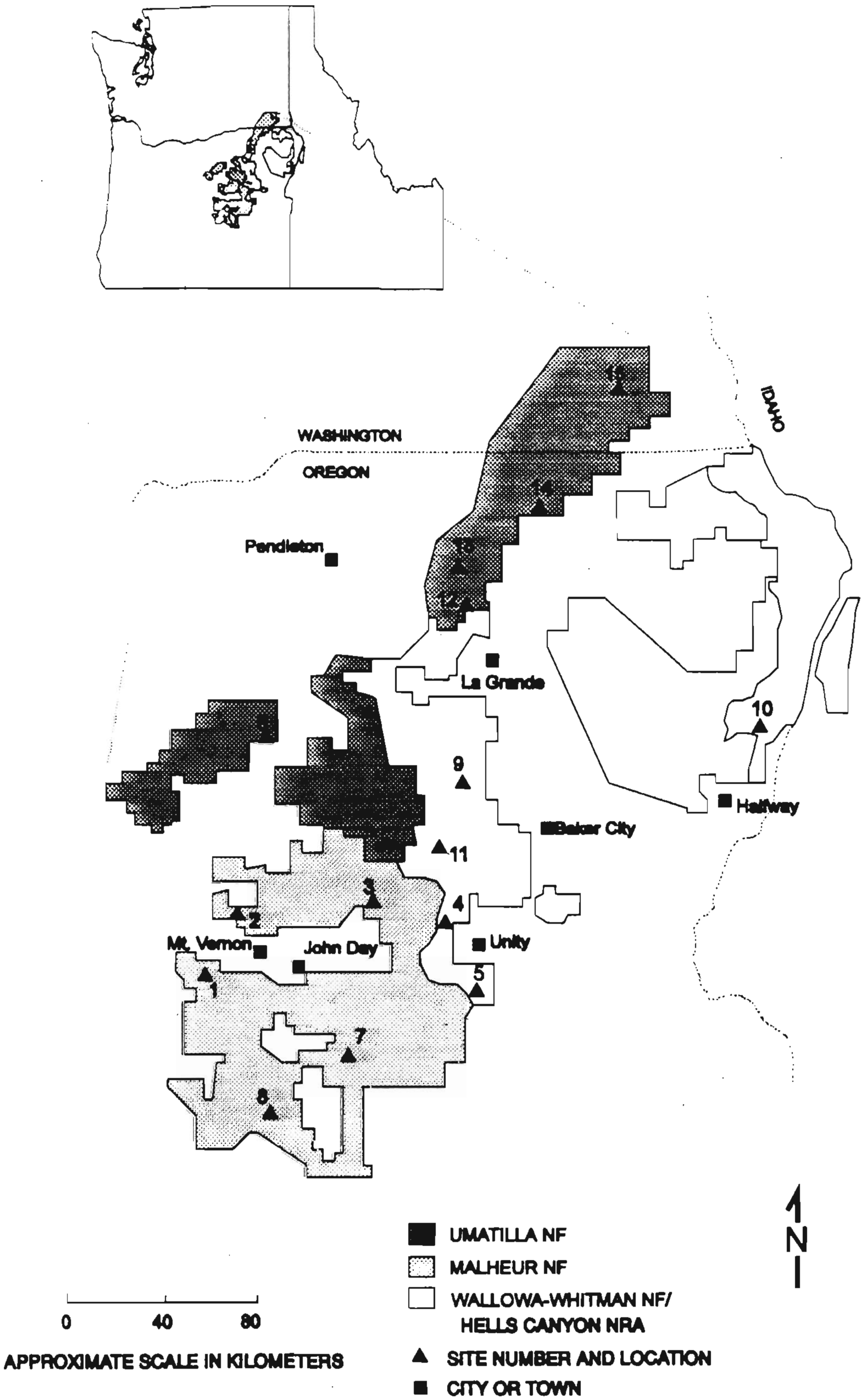


Figure 1. Study site locations.

# Methodology

## Field data collection

Site selection- Sites were selected with the cooperation of U.S. Forest Service personnel. Five sites were established within each of three participating National Forests (Umatilla National Forest, Malheur National Forest, Wallowa-Whitman National Forest/Hell's Canyon National Recreation Area) for a total of fifteen study sites. Each site encompassed an area approximately 500 m x 500 m which satisfied the criteria described below.

The sites were subjectively representative of the vegetation in the area and were within a target range of *Pseudotsuga menziesii* associations to *Abies grandis* associations with a dry understory component. Fourteen sites were composed of a mixture of overstory and understory grand fir and Douglas-fir with ponderosa pine present in the overstory. One site did not include any grand fir. Extreme microsites and topographic or biophysical barriers were avoided if possible. Although all sites had been previously logged, every effort was made to locate sites with minimal harvest-operation disturbance. The presence of fire scars on at least four live trees was a primary consideration for site selection. One site did not satisfy this criterion, but was sampled because of the need for broad geographic coverage.

Plots- Three plots were established at each site, and plot centers marked with 1 cm rebar. One plot was 100 m x 100 m, and two plots were 40 m x 40 m. The vegetation association and physical characters within each plot were consistent, but varied between plots. The 100 m x 100 m plot was the most intensively sampled plot at each site. Plot characters, basal area by species, tree tallies by height and species, herb and shrub cover, and litter and duff measurements were recorded at each plot. In addition, fifty trees were sampled in the 100 m x 100 m plot to determine species and age structure.

Plot characters- Slope, aspect, and vegetation association were recorded at each plot. Vegetation association classifications were based on descriptions by Johnson and Clausnitzer (1992) using the species composition and relative percent cover of overstory trees, understory trees, shrubs, and herbs. A general plot description included unusual features (a sudden shift in vegetation, slope, or aspect), estimated number of harvest entries based on the condition of the stumps, estimated duration of defoliator attacks, and any fire evidence on the site (charcoal, ocular frequency of scarred trees, etc.). Each site was located on a U.S. Forest Service recreation map, and most sites were located on aerial photographs as well. Township, range, and section were recorded at the lab.

Tree tally- Trees were tallied by species in four height classes within three sub-plots centered around each plot center. Height classes were ocularly estimated using the heights of several trees at each plot (calculated using a clinometer and distance from bole) for calibration. Class I trees (0-3 m) were tallied in a 10 m x 10 m sub-plot. Class II (3-10 m) and class III (10-20 m) trees were tallied in a 20 m x 20 m sub-plot, and class IV trees (20 m+) were tallied within a 40 m x 40 m sub-plot. Seedlings were not tallied.

Basal area- A metric-7 basal area factor prism was used to determine "in" trees. "In" trees were tallied by species at each corner and the center of each 40 m x 40 m sub-plot.

Herb and shrub cover- Cover of major herbs and shrubs was ocularly estimated at each plot. Most species were identified to genus level, but not all were identified to species. Not all species on the plot were recorded, although any which were particularly significant in classifying the area were recorded.

Litter and duff- Litter and duff measurements were taken to estimate the amounts of accumulated litter. Any plant material < 6 mm in average diameter which was still distinguishable as plant material and had not started decomposing was considered litter. Duff was the layer of decomposing litter between the litter and mineral soil. Measurements were taken at ten random points in each plot. Litter was measured from the upper surface of any dead and downed material to the interface between the litter and duff layers at each point. The litter and duff measurements were taken from the upper surface of the litter to the mineral soil level.

Age structure data- Age structure data was collected only on the 100 m x 100 m plot. Twenty trees in diameter-at-breast-height (DBH; approximately 1.4 m above ground level) class I (0-15 cm) and twenty trees in DBH class II (16-30 cm) were randomly selected and cored using a "random walk" method. The "random walk" began initially at plot center and thereafter proceeded from the last randomized point using a random distance and azimuth selected from a random numbers table. Allowable distances were between and including 10 m and 15 m. There were no azimuth constraints. If the azimuth/distance values crossed the plot boundary, did not result in locating a tree, or resulted in a tree of an inappropriate size class, new random numbers were selected and the walk continued. Ten trees with the largest DBH over 30 cm and within approximately 20 m of plot center were cored. These trees were not randomly selected.

Species, DBH, diameter at core height, core height above ground, and unusual characteristics (unusual growth, scars) were recorded for each tree cored. Each core was labelled and stored in a plastic straw for transport to the laboratory.

For each species sampled on a plot, two growth samples were collected to determine the number of years between ground height and average core height. The sampled trees were among those located during the random walk. Each tree was destructively sampled and a section of the bole from ground height to 15 cm above ground height was collected. If too few trees <5 cm DBH were encountered during the walk, small trees of that species were sampled in addition to the 50 trees sampled for stand structure.

Fire scar data- Two scar samples from live trees in the 100 m x 100 m plot, and one live scar sample in each 40 m x 40 m plot were collected at each site. We selected scarred live trees which had the most extensive visible fire scar histories on the plot in fair or better condition. Samples were cut as described by Arno and Sneck (1977). Two parallel horizontal cuts 4 to 6 cm apart were made from the center of the scar-face to the cambium on one side of the tree. Cut depth was checked frequently to make sure the sample contained the entire radius of all scars, and to avoid taking a larger sample than needed. Two vertical cuts were made along the back of the parallel cuts from the cambium towards the pith by plunging the chainsaw into the tree. Because we did not include years before the earliest scar in MFRI calculations, not all samples included the pith. Only three samples were collected from one site because we could not locate a suitable fire-scarred tree in the vicinity of the plot.

Laboratory methods

Increment cores- Core samples were mounted in grooved boards and sanded with successively finer grades of sandpaper (#80-220). Annual growth rings were counted using a variable-power microscope with a video monitor display. Boles sampled for growth estimates were sectioned and mounted with the ground-height and 15 cm above-ground-height surfaces exposed. These surfaces were sanded, the rings counted, and the average number of years to attain a height of 15 cm was calculated per species. These adjustments were added to the ring counts for each core. When the pith was not included in a core sample, templates of concentric ring patterns were used to estimate the number of rings to the pith based on ring width and arc (Applequist 1958). Neither the cores nor the growth samples were cross-dated.

Fire scars- Scar samples were sanded with successively finer grades of sandpaper (#80-220), and the rings counted and marked at 10-year intervals using a variable-power microscope. Rings immediately following years in which the cambium was damaged were recorded and ring and scar clarity were noted. These rings were presumed to have been the first year following a fire, unless there was evidence of mechanically-induced scarring. Season of scarring (position of scar within an annual ring) was not recorded.

Samples were cross-dated using ring-width sequences and ring characteristics, especially latewood characteristics. Cross-dating within each site extended the fire occurrence record beyond that contained in a single sample. Two to three ring-sequences were used to cross-reference samples, although the specific sequences sometimes differed between pairs of samples. For example, the sequences used to compare samples A and B may have been different than those used to compare samples A and C. At least one sample per site contained ring-sequences used to compare multiple samples. When discrepancies in ring dates existed between samples, it was assumed that rings were locally absent and years were adjusted to the earliest date associated with a specific ring or ring sequence (Stokes and Smiley 1968). All sample dates were adjusted by the same amount, which ranged from 0 to 4 years.

Once year adjustments were made, years of fire occurrence were compared between samples. Fire years which differed by 1 to 2 years were examined and evaluated based on scar quality and ring patterns to determine whether or not they represented the same event. These adjustments were made to refine the initial cross-dating adjustments. Years were adjusted either to the year associated with the highest-quality scar, or to the sample with the most consistent ring record. At least one adjustment was made at each site. The resulting fire occurrence years were combined into a master fire chronology for each site (Dieterich 1980). Because this study focused on the intervals between fires, rather than exact years of fire occurrence, fire scars were not cross-dated between sites.

In addition to the site for which only three scar samples were collected, two scars from one other site, and one scar from a third site could not be processed because of poor sample quality, so fire frequency may be more conservative at these sites (sites 12, 13, and 3, respectively) than at other sites.

Data analysis

Age structure data- Annual ring counts from the increment core samples (approximately 50 per site) were used to construct a histogram of ten-year age classes by species for each site. This information was used in conjunction with stand development ideas (Oliver and Larson 1990) and species characters to describe stand development and infer development patterns in the context of the fire history at that site.

Basal area data- Basal area ($m^2$/hectare) was calculated for each plot to characterize the basal area contribution of tree species in each plot.

Tally by height and species- Tree tallies were used to characterize the vertical structure and relative abundance of species in each plot per hectare. This tally was also used in conjunction with the species and age histograms to describe stand structure for each 100 m x 100 m plot.

Fire scars- Mean fire return intervals (MFRIs) were calculated for each site using the fire-return intervals from each master fire chronology. MFRIs were calculated for the period between the earliest recorded fire, and the most recent fire. The total number of years between these scars was divided by the number of fire-free intervals (number of scars - 1) to yield the MFRI at a site. Years previous to the earliest scar, or following the most recent scar were not included in MFRI calculations.

The master chronologies represent all recorded fire events contained in the scar samples at each site (4 per site). No assumptions were made about the possible effects of fire suppression on fire frequency. The MFRIs and associated sample standard errors were qualitatively compared between sites by slope, aspect, elevation, site moisture, and geographic location. The method was simply to order the sites using the character being compared (e.g. slope) on the abscissa, plot the MFRI's and sample standard error bars on the ordinate, and visually inspect the plot for trends. Ordering the sites according to slope, elevation, and geographic location was straightforward, and was based on slope degree, elevation, or geographic position, respectively. The order of sites by moisture was based on site species composition and vegetation association descriptions in Johnson and Clausnitzer (1992). Aspect was ranked from the lowest values to the highest values. However, because high aspect values are similar to low aspect values (e.g. 360° = 0°), northerly aspects are towards the extremes of the abscissa, and southerly aspects are towards the center.

Fire return interval variability was compared across sites using a non-parametric squared ranks test for variances (Conover 1980) (Appendix C). This tested the null hypothesis that "variance is not different among sites". A non-parametric analysis of variance was not employed because several sample sizes (the number of fire-return intervals at a site) were too low ($n < 4$, at 4 sites), and sample sizes were widely disparate ($n$ ranged from 2 to 16).

In the squared-ranks test for variance, the absolute deviation from the appropriate site MFRI was calculated for each fire-return interval ("observation"). The deviations were combined from smallest to largest and assigned a rank. When two or more deviations had the same value, an average rank was assigned to each. The square of these ranks was used to compare the variance of fire frequency between sites. The comparisons were based on deviations from the mean, instead of actual fire-return intervals, so that the results would not be influenced by differences in the magnitude of MFRIs and variances among sites.

A non-parametric multiple comparison (Zar 1984) was used to detect significant differences in fire frequency between sites (Appendix C). As in the squared ranks test for variances, deviations from the mean were ranked and used in subsequent calculations. Sites were compared based on the mean-rank calculated for each site. Sites were grouped when the null hypothesis ($H_o$: fire frequency is the same at every site) was not rejected. The resulting groups were examined for physical, geographic, or moisture gradient consistencies which might explain trends in fire frequency variability.

## Results and discussion

### Fire frequency

Mean fire-return intervals are often the focus of fire history studies. While a mean provides a simple basis for fire frequency comparisons between sites, it does not directly describe the variability with which fire burns at a site. Fire frequency variation is important because it creates and enhances plant species and age diversity within forests (Cooper 1960, Heinselman 1973, Agee 1981). Landscape and forest diversity affect wildlife habitat and forage conditions, the spread of insect and disease outbreaks, and the impacts, extent, and probability of occurrence of some disturbances (Agee 1981, Romme 1982, Pickett and White 1985, Knight 1987).

In this study, the number of fires recorded at each site varied from 3 to 17 (Table 1). MFRIs ranged from 9.9 years to 49.0 years with sample standard errors ranging from 4.8 years to 41.6 years. Frequent fires appear to have decreased in the early 20th century, although fire scars at sites 2, 6, 12, and 14 indicate that fires have occurred at those sites in the past 60 years (Appendix B). The fire frequencies reported in this study are similar to those reported in other studies conducted in similar forest types (Table 2).

Comparisons of fire frequency variances using a non-parametric squared ranks test ($H_0$: variance is not different between sites) was rejected at $p = 0.05$ (Conover 1980). The non-parametric multiple comparison of fire frequency (Zar 1984) resulted in groupings of sites with similar return intervals (Appendix C). However, there was overlap between groupings, resulting in one group of 9 sites, and 6 individual sites. There did not appear to be a relationship between elements within groups which explained the aggregations.

Elevation, slope, aspect, vegetation, and disturbance history interact and influence fire occurrence at a site (Brown and Davis 1973, Heinselman 1973, Agee 1991). In this study, sample sites were constrained to a range of vegetation types bounded by *Pseudotsuga menziesii* and dry *Abies grandis* associations where ponderosa pine is co-dominant, but slope, aspect, and elevation were allowed to vary. It was expected that sampling within a narrow range of vegetation associations would reduce the amount of variability associated with vegetation types and result in patterns of fire occurrence related to topographic or geographic features.

Table 1. Fire frequency data per site.

| Site | Fire years | MFRI (years) | Standard error (years) | Range of intervals (years) |
|---|---|---|---|---|
| 1 | 1899,1894,1890,1853,1848,1833,1826, 1814,1806,1797,1786,1777,1767 | 11.0 | 8.8 | 4 - 37 |
| 2 | 1946,1921,1900,1894,1888,1878,1874, 1869,1851,1845,1834,1811,1758 | 15.7 | 14.0 | 4 - 53 |
| 3 | 1889,1847,1799,1742 | 49.0 | 7.5 | 42 - 57 |
| 4 | 1923,1889,1870,1863,1856,1846,1829, 1804 | 17.0 | 10.0 | 7 - 34 |
| 5 | 1900,1887,1855,1846,1822,1760,1641 | 43.2 | 41.6 | 9 - 119 |
| 6 | 1934,1921,1910,1907,1893,1879,1867, 1861,1853,1838,1834,1831,1822,1802, 1794,1783,1776 | 9.9 | 4.8 | 3 - 20 |
| 7 | 1901,1886,1851,1846,1830 | 17.8 | 12.5 | 5 - 35 |
| 8 | 1889,1875,1855,1847,1831,1821,1816, 1795,1772,1751 | 15.3 | 6.5 | 5 - 23 |
| 9 | 1877,1873,1845 | 16.0 | 17.0 | 4 - 28 |
| 10 | 1913,1911,1902,1894,1885,1880,1871, 1854,1844,1834,1805,1793,1790,1784 | 9.9 | 6.9 | 2 - 29 |
| 11 | 1918,1902,1882,1866,1846,1798 | 24.0 | 13.6 | 16 - 48 |
| 12 | 1976,1908,1890,1869,1853,1839,1791 | 30.8 | 22.1 | 18 - 68 |
| 13 | 1899,1890,1867,1839,1800 | 24.8 | 12.4 | 9 - 39 |
| 14 | 1940,1904,1890,1884,1870,1848,1833, 1813,1808,1779,1746 | 19.4 | 10.7 | 5 - 36 |
| 15 | 1919,1908,1879,1872,1868,1858,1848, 1824,1821,1818,1812,1804,1794,1781 | 10.6 | 7.8 | 3 - 29 |
| | Overall mean fire frequency and standard error: | 17.3 | 16.0 | Range of MFRIs: 9.9 - 49.0 |

Table 2. Fire frequencies documented in studies in ponderosa pine and mixed-conifer forests. Ranges represent the range of MFRIs from individual trees or clumps of trees within the study areas. An asterisk (*) denotes a range based on the fire return intervals recorded on one scar sample.

| Forest type | MFRI range (years) | Elevation (m) | Location | Reference |
|---|---|---|---|---|
| mixed-conifer | 9 - 42 | 1700 - 2100 | Sierra Nevada, CA | Kilgore and Taylor (1979) |
| mixed-conifer | 9 - 28 | 1340 - 1550 | Crater Lake National Park, OR | McNeil and Zobel (1980) |
| mixed-conifer | 12 - 59 | 1200 | Kinney Creek, OR | Agee (1991) |
| ponderosa pine | 2 - 53 | 1550 | Pringle Falls, OR | Mazany (1983) |
| ponderosa pine | 11 - 47 | 600 - 1050 | Warm Springs Reservation, OR | Weaver (1959) |
| ponderosa pine/ mixed-conifer | 6 - 55 | 600 - 1400 | Warm Springs Reservation, OR | Soeriaatmadja (1966) |
| mixed-conifer | 40 - 133 | 1650 - 1750 | Elkhorn Mountains, OR | Bork (unpubl. data) |
| grand fir | 50 - 200 | 1600 - 1700 | | |
| ponderosa pine/ mixed-conifer | 6 - 38* | not indicated | Blue Mountains, OR | Hall (1976) |
| mixed-conifer | 7 - 67 | 900 - 1170 | Wenatchee Valley, WA | Wischnofske and Anderson (1983) |
| ponderosa pine/ mixed-conifer | 3 - 30 | 1050 - 1600 | northern Rockies | Arno (1980) |
| grand fir | 25 - 250 | | | |

Studies in which fire frequency was sampled across elevation gradients in southern Oregon (McNeil and Zobel 1980, Agee 1991), and the northern Rocky Mountains (Arno 1980) showed inverse relationships between elevation and fire frequency; as elevation increased, fire frequency generally decreased. However, inferring the influence of elevation on fire frequency is confounded by the close association between changes in elevation, dominant overstory, and rates of litter accumulation in these studies.

Ordering sites according to elevation, and comparing fire frequencies did not result in a gradient of fire frequencies in this study (Figure 2). This may indicate that the elevation range among sites was too narrow (1070 m to 1830 m) to produce differences in fire frequencies. Or, the effects of elevation on fire frequency may not have been apparent because of interactions with other factors, such as ignition probability or surrounding forest types.

General forest cover and landforms follow a north-to-south trend in the Blue Mountains. In the southern and central Blue Mountains, forests occur in mountainous areas separated by wide river basins. In contrast, forests in the northern Blue Mountains occur mainly on the sides of river canyons, and on the intervening plateaus. Because of these topographic differences, lightning strike probability and fire ignition might be expected to differ between the northern and central/southern Blue Mountains. Limited data relating lightning strikes and ignitions in the Blue Mountains showed slight trends in strike probability and fire occurrence, favoring the central and southern Blue Mountains (Morris 1934). However, comparisons of fire occurrences among sites along a north-to-south gradient yielded no patterns in fire frequency or frequency variability in this study (Figure 2).

MFRIs and frequency variability were also compared among sites from east-to-west, although there were no obvious floristic or landform gradients associated with this ordering. Once again, the plot of MFRIs did not reflect a gradient based on geographic position (Figure 2).

Slope and aspect influence vegetation patterns at a site, and consequently, fuel loads and stand flammability (Barbour et al. 1987). Species which are commonly associated with moister conditions often establish on north-aspect slopes, while more drought-tolerant species establish on south- and west-aspect slopes (Minore 1979, Romme and Knight 1981, Agee and Kertis 1987, Barbour et al. 1987). Slope angle also affects microsite conditions, influences

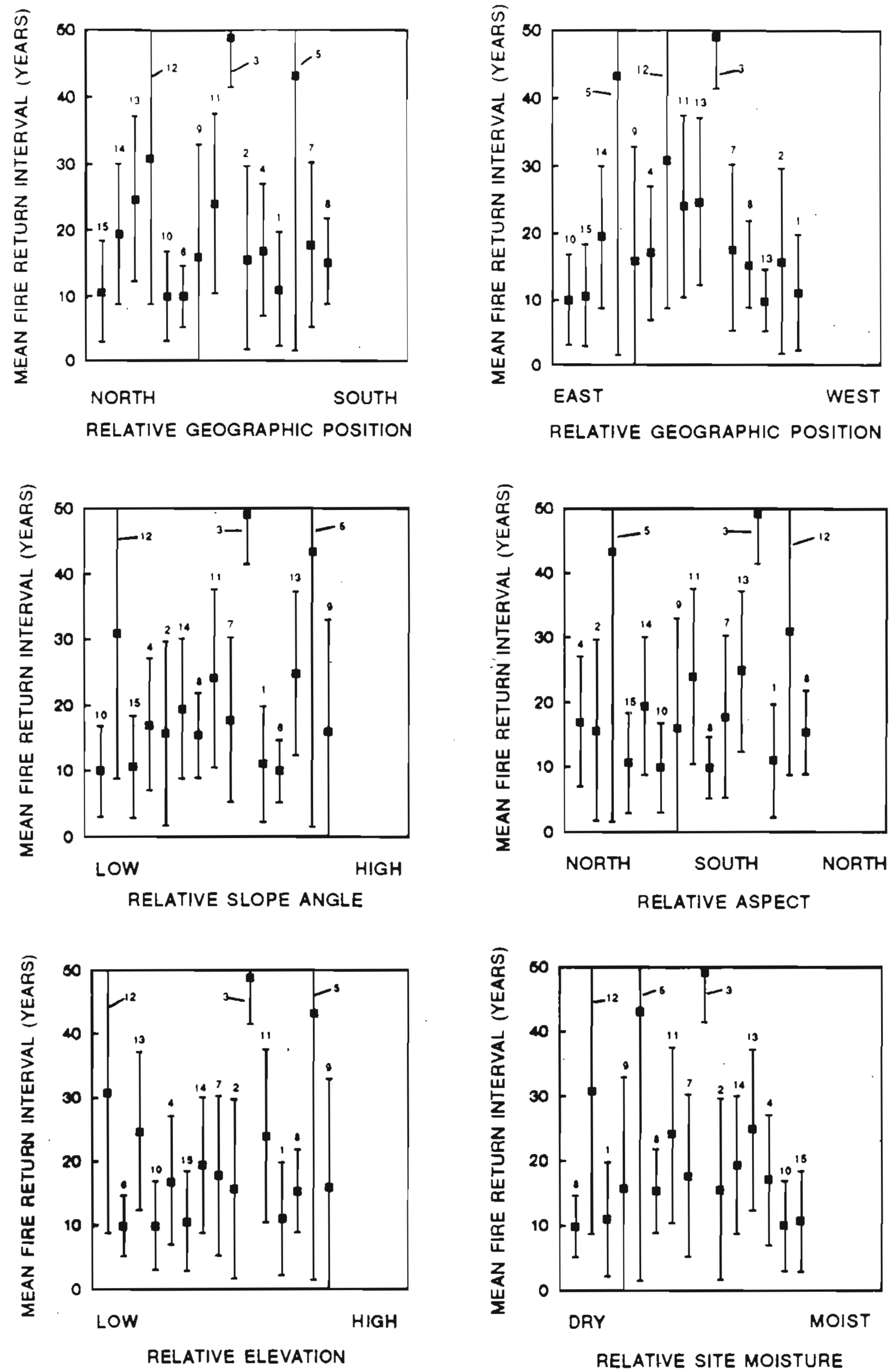


Figure 2. Comparisons among sites based on physical and floristic features. MFRIs are represented by a small square, with symmetric standard error bars about the mean. Asymmetric error bars are an artifact of graph scaling.

species establishment (Barbour et al. 1987), and directly influences fire spread and intensity (Brown and Davis 1973, Agee 1993).

The amount of solar radiation a site receives varies directly with exposure. South- and west-facing slopes receive greater total solar insolation than northern-facing slopes (Barbour et al. 1987). A consequence of this insolation is that fuels on south- and west-facing slopes have lower fuel moistures than those on north-facing slopes. Differences in fuel moisture directly influence fire behavior and effects (Brown and Davis 1973, Williams and Rothermel 1992). Comparisons among sites in the Blue Mountains based on slope, aspect, and general site moisture did not produce patterns in MFRI or variability (Figure 2).

In addition to the interacting effects which elevation, slope, aspect, and vegetation have on fire frequency, human influences may have affected the documented fire frequency. Humans have inhabited regions in the inland Pacific Northwest, including the Blue Mountains, for thousands of years (Shinn 1980). Although the effects of the presence and practices of these early inhabitants can only be inferred, they undoubtedly modified the vegetation and influenced vegetation development (Shinn 1980). During the mid-1800's, settlers from the eastern United States travelled westward along the Oregon trail, and several other trails which passed through the Blue Mountains (Evans 1990). Although many of these travellers did not settle in the Blue Mountains, those who remained in the Blue Mountains influenced vegetation patterns and development through the intentional ignition or suppression of fires, as well as through land-use modification (Hall 1976, Shinn 1980). Historic human presence was confirmed at only one site (site 12), which was adjacent to the Whitman trail (Evans 1990). Because of the unknown nature and extent of the possible impacts at site 12, and the lack of evidence of historic impacts at other sites, all sites were considered to have been equally influenced by human activity.

Although records of historical land use were not available for the sites, possible land-use influences deserve mention. At every study site, there was evidence of current domestic livestock grazing and selective timber harvest. Domestic livestock grazing has occurred in the Blue Mountains since the early 1900's (Hall 1976), and remains a present-day livelihood. Grazing reduces fuel loads, and consequently limits fire frequency and spread (Cooper 1960, Madany and West 1983, Arno and Gruell 1986, Stein 1988). The extent and intensity of grazing and timber harvest in the vicinity of the study sites was unknown, and possible effects were not incorporated in the interpretation of the results.

Stand structure

Age frequency histograms, tree tallies, basal areas, and fire occurrences are presented by site in Appendix B. General stand structure was similar between sites (Figures 3, 4, 5). Grand fir and Douglas-fir were the dominant species for height classes < 20 m, while ponderosa pine dominated height classes >20 m (Figure 3). Basal area estimates at each plot also reflected this structure of a ponderosa pine overstory with an understory consisting primarily of grand fir and Douglas-fir (Figure 4).

Most sites exhibited a peak in tree establishment in the past 100 years (Appendix B). Ponderosa pine dominated age classes >200 years, but was present throughout all age classes at most sites (Figure 5). Grand fir and Douglas-fir were rarely present in the oldest age classes (>200 years), but were well represented in age classes younger than 200 years.

Changes in stand structure in the absence of fire have been used to infer the impact of frequent, low-severity fires in forests where ponderosa pine is dominant or co-dominant. Field studies (Weaver 1959, West 1968, Houston 1973, Dickman 1978, Kilgore and Taylor 1979, Parsons and DeBenedetti 1979, Hall 1981) and computer simulations (Kercher and Axelrod 1984, van Wagtendonk 1985, Keane et al. 1989) document increases in fire-intolerant species following a reduction in fire frequency.

The stand structure and fire history at 8 of 15 sites in this study was consistent with this development pattern (Appendix B). This stand structure reflects at least two different, but related influences of fire on species composition: tree survival, and tree establishment (Zwolinski 1988, Kauffman 1990). In the presence of frequent low-intensity fires, ponderosa pine saplings are protected by thick bark and vertical fuel discontinuity (Flint 1925, Habeck and Mutch 1973, Minore 1979, Hall 1981). Grand fir and Douglas-fir saplings have thinner bark and more continuous fuel ladders, both of which predispose these species to death by fire when young. In the absence of fire, tree survival depends more on resource competition than on bark thickness or growth form, and trees which may not have survived in the presence of fire are able to persist (Habeck and Mutch 1973, Wright 1978).

As a stand develops and the canopy closes, conditions favor the establishment of shade-tolerant trees (Oliver and Larson 1990). Often, as in the stands sampled in this study, these shade-tolerant trees (grand fir and Douglas-fir) are also fire-intolerant species until maturity (Flint 1925, Starker 1934, Harmon 1984). Because of this, changes in establishment

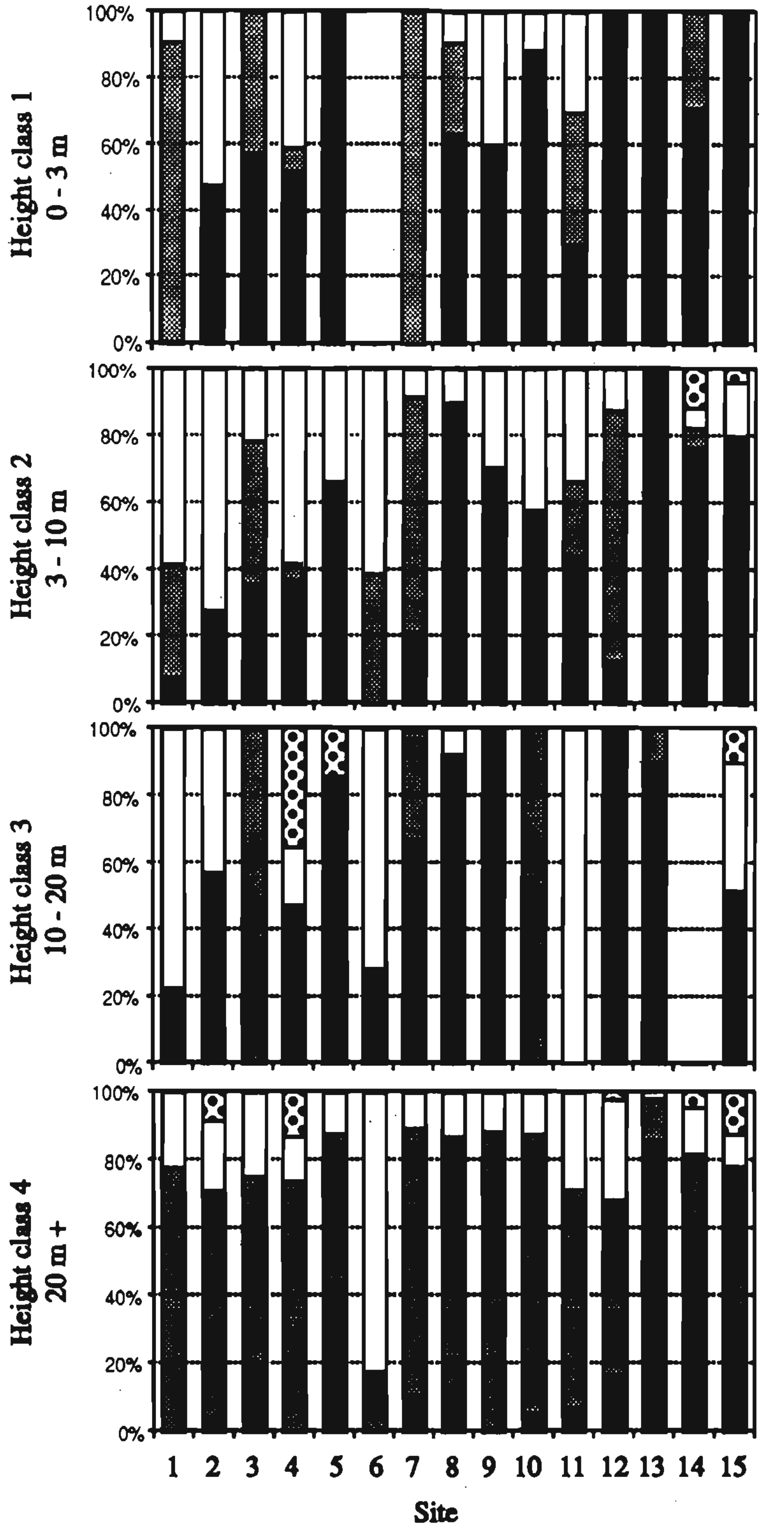


Figure 3. Relative percent trees/ha by species for each study site. Number of trees/ha extrapolated from tree counts in smaller sample plots. ■ grand fir ■ ponderosa pine □ Douglas-fir ▩ western larch

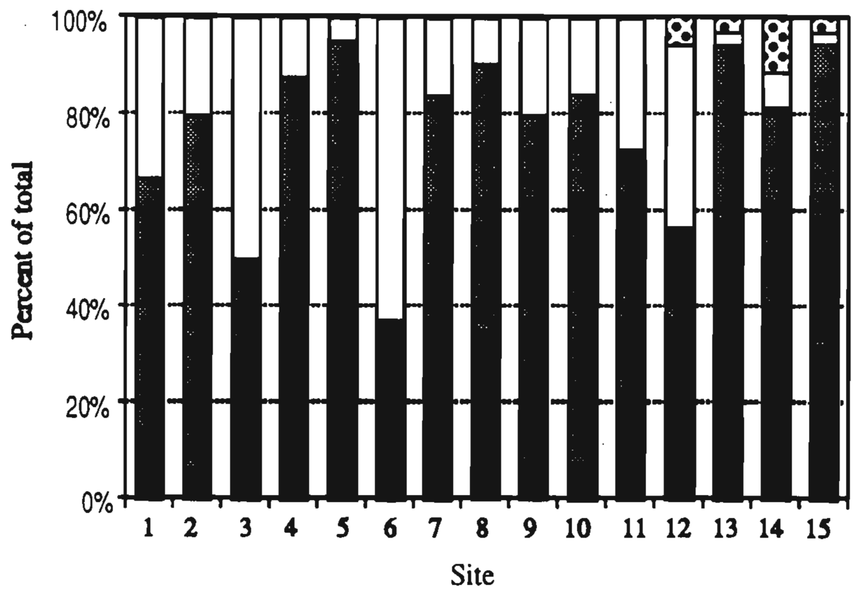


Figure 4. Relative basal area by species for each study site. grand fir ponderosa pine Douglas-fir western larch

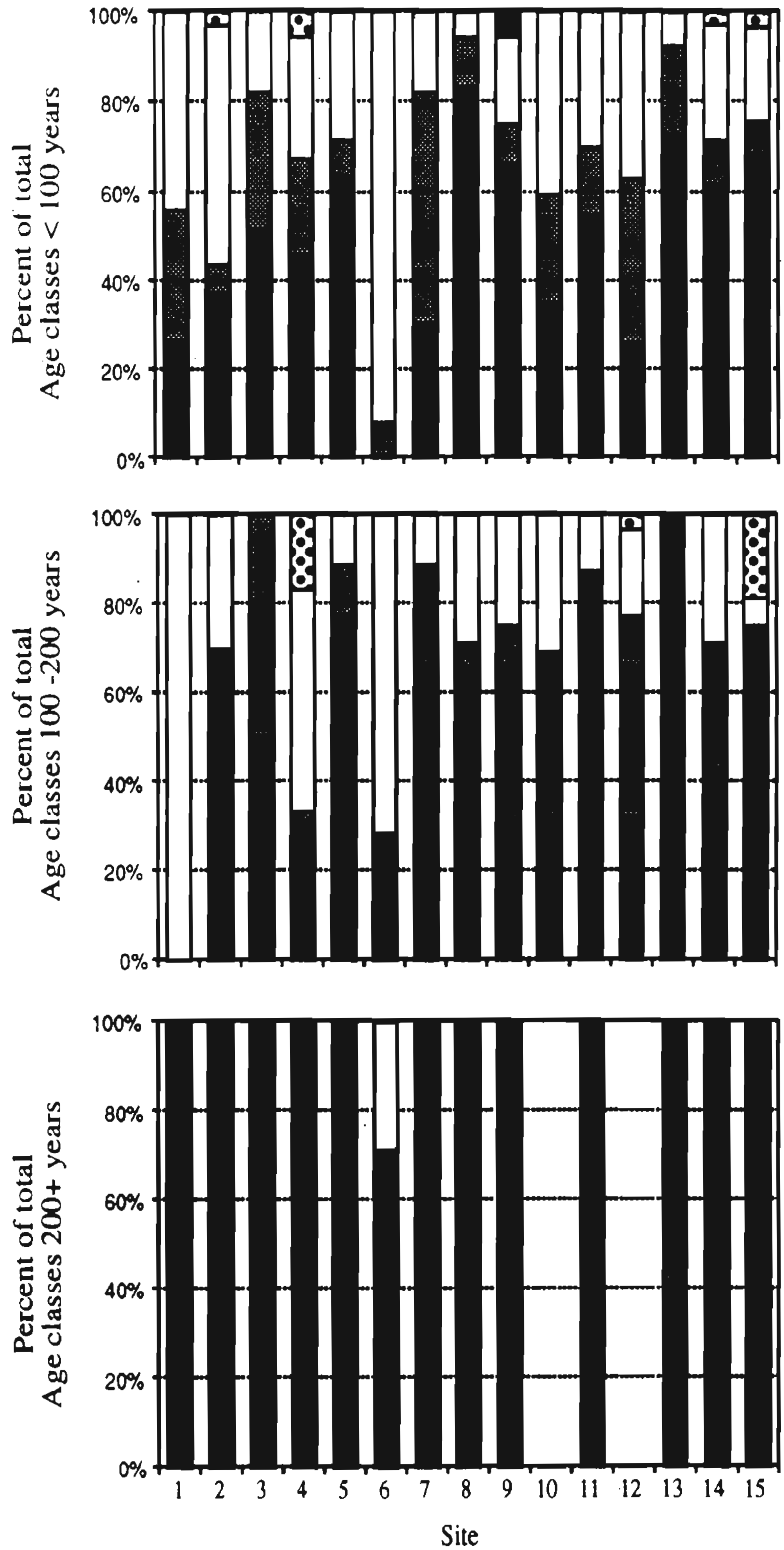


Figure 5. Relative percent establishment by age class and species for each study site.
grand fir ponderosa pine Douglas-fir western larch lodgepole pine

patterns caused by canopy closure accentuate the relative increase in survival of fire-intolerant species in the absence of fire.

Seven of 15 sites (sites 2, 4, 6, 12, 13, 14, 15) showed peaks of establishment of fire-intolerant species amidst years of fire occurrence (Appendix B). Such patterns are not as commonly documented as are decreases in establishment of fire-intolerant species during periods of frequent fires. Fire frequency, fire severity, fire spread, regeneration patterns, or other influences may contribute to peaks of establishment of fire-intolerant species during periods of frequent fires.

Fire frequency plays a role in species establishment and survival (Romme and Knight 1981, Zwolinski 1988, Kauffman 1990, Agee 1991). While frequent fires may not prevent establishment of late-seral, fire-intolerant species (Woodard in press), survival of these trees may be limited by fire (Habeck and Mutch 1973). The principal tree species in this study (grand fir, Douglas-fir, ponderosa pine) become more fire-tolerant with age and size (Harmon 1984, van Wagtendonk 1985, Peterson and Ryan 1986). If sufficient time exists between seedling establishment and the next fire, bole diameter and bark thickness will have increased, and saplings will have an increased possibility of survival in subsequent low-intensity fires (Harmon 1984). Sites 4, 6, 12, 14, and 15 exhibited peaks of establishment of shade-tolerant species between fires (Appendix B). The periods between successive fires, during which the peak establishments occurred, ranged from 14 to 34 years. This would have been sufficient time for Douglas-fir and grand fir to develop enough fire resistance to survive the next low-intensity surface fire (Harmon 1984).

Differences in fuel load, topography, and local climatic conditions during a fire create fire severity and spread patterns which are not uniform throughout a burned area (Brown and Davis 1973). Because of this variability, individual trees or patches may effectively experience longer fire-free intervals than other trees or areas within the same overall burn perimeter. The factors influencing establishment and survival previously discussed would apply within these unaffected areas, and might be reflected in the stand structure. Fire patchiness contributed to stand structures in which fire-intolerant species survived fires in *Abies magnifica* (red fir) forests (Pitcher 1987, Taylor and Halpern 1991, Taylor 1993), and subalpine forests (Woodard in press). In this study, a peak of establishment of fire-intolerant species occurred at site 2 between fires which were 6 years apart (Appendix B). It is possible that the trees which are represented in this establishment pulse survived the next fire because of fire patchiness.

Historical fire severity was not directly addressed in this study, but may be inferred using stand structure and species characteristics. The presence of large, old ponderosa pines, and occasional old grand firs and Douglas-firs in the overstory indicates that historical fires were likely low- to moderate- severity. However, severity was probably patchy, as reflected in the stand structures at study sites 2, 4, 6, 12, 13, 14, and 15.

Sampling design considerations and influences

Sampling design and scale are very important to consider when inferring the role of fire in forest development. These factors do not influence the information present at a site, but may have a large effect on the information researchers collect, and how the data are interpreted. For example, site selection was based on the presence of fire scars, and stand structure. These criteria not only ensured the presence of low- to moderate-severity fires, but also biased the sites towards stands in certain successional stages of development often associated with the absence of fire. These biases do not necessarily challenge the validity of the fire history data, but narrow the scope of inference to which the data may be applied.

Because of the variability of fire spread and intensity, it is probable that some fire events were not documented in this study. Trees either may not have been scarred, or previous scars may have been burned out by subsequent fires and may not have been distinguishable as fire scars. When scars are "lost", fire return intervals based on the remaining scars are longer than actually existed. Although a more complete fire record might have been obtained by sectioning or felling any fire-scarred trees on the site, logistical and ethical issues limited the amount of destructive sampling in this study. Because of these factors, the fire chronologies were limited to the fire events contained within the sample wedges, and are conservative estimates of the occurrence of fire at each site

Sampling fire occurrences at the appropriate scale is important in fire history studies. If the area sampled is similar to or smaller than the extent of average-sized fires, the resulting master fire chronology is likely to be representative of fire occurrence across one point (Arno and Petersen 1983, Agee 1993). However, because the possibility of detecting different fires increases as the area sampled increases, sampling an area larger than the extent of average-sized fires results in an area frequency, rather than a point frequency (Kilgore and Taylor 1979, Arno and Petersen 1983, Agee 1993). Misinterpretation of the influence of fire on stand development might occur if a fire chronology is assumed to represent a point frequency when it does not.

Likewise, sampling age and species composition in a stand involves an awareness of scale and forest patterns. Patterns of tree clumping have been noted at different scales in ponderosa pine forests (Weaver 1961, Wooldridge and Weaver 1965, Cooper 1960, White 1985). The scale at which these patterns are important is partially determined by the objectives of a study. For example, sampling within a clump might be appropriate if the research objective is to determine the earliest establishment date within the clump, but may not be suitable for inferences about a larger area.

Effectively combining fire frequency information with stand age and species information to infer the influence of fire on stand development, relies on the compatibility of the scales of inference. Ideally, fire extent would provide general guidelines about the appropriate scale at which to sample fire occurrence and stand structure. The influence of fire on stand development might be misrepresented if age structure information is derived from an area much larger than the area considered for the point frequency.

In this study, age distributions described the stand structure of the intensively sampled 100 m x 100 m plot at each site, while fire scar chronologies included the two 40 m x 40 m plots. The sampling strategies were assumed to be representative of fire frequency and stand structure at each site, although stand structure was sampled over a smaller area than fire frequency. Because of the variability with which fire burns, it is possible that some fires recorded at a site (areas up to 500 m x 500 m) did not burn any portion of the central 100 m x 100 m plot at that site. This could lead to a stand structure in which fire-intolerant species appear to persist throughout periods of frequent fires, such as at sites 2, 4, 6, 12, 13, 14, and 15 (Appendix B).

An additional factor which may have influenced stand structure patterns is the sampling design used to create the species and age distributions. In this study, age distributions represented three diameter classes of trees which were at least 1.4 m in height (DBH classes: I = 0-15 cm, II = 16-30 cm, III = 30+ cm). Trees which were not 1.4 m in height were neither cored, nor included in plot basal area tallies, but were represented in plot tree tallies by height. Stumps and dead trees were not sampled for the age distribution, but were included in both the basal area and tree height tallies. Thus, the absence of trees which were harvested or dead, and trees which were <1.4 m in the age histograms is a result of the sampling scheme and does not necessarily reflect the absence of trees in those classes on the plot. The exceptions to this were those trees sampled to obtain growth estimates, in which case the trees may have been <1.4 m in height. Whether or not including trees <1.4 m in height in the age distribution analysis would have affected the results is difficult to determine without having sampled them.

Inferring forest stand development begins with identifying physical and floristic factors which might have influenced tree establishment, survival, or death. It soon becomes apparent that there is a myriad of scenarios leading to the current stand structure, even when recorded events, such as fires, are incorporated. Sampling design and scale influence what data are collected, and therefore, limit the inferences which can be made about a stand. Equally as important to consider as the data which were collected, are the data which were not collected. Pilot studies may reduce the gap between relevant information which is sampled, and that which is not. This study, as well as other retrospective studies, is most appropriately viewed as an exploratory and inferential study, rather than as a definitive history.

## Management implications

A fire history study provides insights about how fire has influenced the forests we see today. The persistence or absence of certain species in a forest may be linked to the characteristics of fire (frequency, severity, extent) in that forest. Structural characteristics, such as vertical fuel continuity, or stand patchiness are also influenced by the presence or absence of fire. Understanding the influences which fire exerts on a forest is important for understanding the implications of "managing" fire in forests through activities such as fire suppression or prescribed burning.

Fire frequencies in this study showed no visible trends in MFRI or frequency variability associated with physical or floristic characteristics of the sites (Figure 2). Because of this variability, it is difficult to generalize about the presence of fire in mixed-conifer forests in the Blue Mountains based solely on the physical characteristics or geographic location of a site. While this may be an artifact of the sampling design, it may indicate that the frequency of fire within mixed-conifer forests in the Blue Mountains is more related to that vegetation type than physical factors. This provides some planning flexibility for managers who desire to incorporate fire into management plans for mixed-conifer forests. In a brief discussion on the possible influences which varying environmental conditions have had on fire frequency and forest structure in mixed-conifer forests in the past 10,000 years, Parsons (1990) states:

> "From a management perspective, the greater the variance in natural fire frequency, fire intensity, fuel loading or forest structure, the less important it is to accurately reconstruct ecosystem structure or processes known to have occurred at any given point in time".

The importance of accurately "reconstructing" fire frequency or stand structure also depends on the management goals (structure- or process-related goals), and the scale at which this management takes place. Managing for particular forest structures has more predictable results than reintroducing a process (frequent fire) to a forest (Agee and Huff 1986). Because of changes in fuel load and stand structure in mixed-conifer forests since the time documented in fire histories, simply mimicking historical fire frequency (process-oriented goal) is not equivalent to restoring the historical effects of these fires on stand structure (Agee and Huff 1986, Parsons 1990).

The present forest structure documented at sites in this study would promote higher-severity fires than historical fires because of greater fuel loads and vertical fuel continuity between the forest floor and the canopy (Kilgore and Sando 1975, Hall 1976, Kilgore and Taylor 1979, Parsons and DeBenedetti 1979, van Wagtendonk 1985). As a result, species compositions and landscape patterns may be different than they were historically, and may be unacceptable for current management desires.

Managing forests on a small scale (several hectares) requires a different management approach, and has different implications on defining realistic management objectives than managing forests on a larger scale (hundreds to thousands of hectares). For example, a mixed-conifer stand for could be "restored" to the historical forest structure of overstory ponderosa pine with an open, grassy understory by thinning the stand, followed by prescribed burning (Agee and Huff 1986, Biswell 1989). Such a specific goal seems realistic for a small area. However, if the area managed is large, it may not be logistically feasible, nor ecologically desirable for all stands to be similar in structure.

Based on the fire frequency in some stands in this and other studies (Hall 1976, Bork unpubl. data), as well as descriptions by early visitors to the Blue Mountains (Evans 1990), ponderosa pine forests with relatively open understories were probably common in the Blue Mountains. However, because all fires in ponderosa pine and mixed-conifer forests are not equal in frequency, extent, or severity, some stands would have been more open than others, and a mosaic of stand ages and structures would have existed over a landscape. It is likely that an overall landscape equilibrium (Bormann and Likens 1979) existed between ponderosa pine and mixed-conifer stands with very open, "average", and dense understories. Therefore, structural management objectives at a landscape scale might focus on achieving a mosaic of stands representing various stages of development, rather than creating and maintaining a specific structure across the landscape.

Retrospective studies enhance our understanding of forest development processes and may aid management decisions. However, it is important to recognize that the structures and processes documented in such studies reflect the accumulated effects of many influences at a single instant in time, and often at a localized point on a landscape (Sprugel 1991). It is impossible to identify and understand all of the influences which have shaped our forests because environmental conditions are constantly in flux. Therefore, accounting for, and managing the temporal component of forest development is difficult, perhaps impossible, to achieve. However, recognizing that the factors influencing forest development change with time is important to consider when formulating forest management goals because such variability implies that the forest structures or processes captured at one point in time may be no more "natural" (and thus no more suited to defining management goals) than at another point in time. As Sprugel (1991) states: "Every point in time is special".

Incorporating historic information into current management strategies requires careful thought and consideration of past and present forest conditions. The conditions under which the documented fires occurred may have been different than those we observe today. Likewise, conditions will change in the future. Because of these considerations, clearly identifying management goals is as essential as understanding the historic role of fire when formulating management plans.

## Research needs

This study surveyed fire frequency within "mixed-conifer" forests in the Blue Mountains. Because fire frequencies were based on the time between fires, rather than exact years of fire occurrence, fire scar samples were ocularly cross-dated within sites, but were not cross-dated between sites. A study in which the exact years of fire occurrence were identified would provide an opportunity to examine possible relationships between fires and climate (e.g. Keen 1937), insect or disease outbreaks (e.g. Swetnam and Lynch 1993), or changes in fire frequency over time (e.g. Masters 1990) in the Blue Mountains. Although historical changes do not predict the likelihood or direction of future change, detecting such trends, and identifying possible contributing factors enhances our understanding of forest processes and development.

Since fire frequency is so variable, further investigation of fire extent in mixed-conifer forests in the Blue Mountains might elucidate differences which would be useful for planning prescribed burns intended to mimic historic fire occurrences. Such a study might include data about the extent of the mixed-conifer type along topographic or geographic gradients, the average stand size, and the size of fires in the mixed-conifer type. Comparing the average fire extent (area burned in an average fire in a mixed-conifer forest) and relative fire extent (percent of mixed-conifer forest burned in an average fire) along physical gradients might reveal differences useful for characterizing fire occurrences in the Blue Mountains.

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**Appendix A.** Site locations.

Four-letter vegetation association codes are based on Johnson and Clausnitzer (1992). Common names are enclosed in parentheses.

ABGR = *Abies grandis* (grand fir)
CAGE = *Carex geyeri* (elk sedge)
CARU = *Calamagrostis rubescens* (pinegrass)
LIBO = *Linnaea borealis* (twinflower)
PSME = *Pseudotsuga menziesii* (Douglas-fir)
SPBE = *Spiraea betulifolia* (birchleaf spiraea)
VAME = *Vaccinium membranaceum* (big huckleberry)
VASC = *Vaccinium scoparium* (grouse huckleberry or whortleberry)

Table A1. General site locations and descriptions. Characteristics describe the 100 m x 100 m plot at each site.

| SITE | LOCATION | VEGETATION ASSOCIATION | ELEVATION (meters) | ASPECT (degrees) | SLOPE (degrees) | RELATIVE SITE MOISTURE |
|---|---|---|---|---|---|---|
| 1 | Widow's Creek | PSME/CAGE | 1520 | 235 | 21 | moderately dry |
| 2 | Raddue | ABGR/VASC | 1520 | 20 | 11 | moderately moist |
| 3 | Dixie Butte | ABGR/CARU | 1600 | 235 | 18 | moderately dry |
| 4 | Seed Orchard | ABGR/SPBE | 1310 | 7 | 9 | moist |
| 5 | E. Camp Creek | ABGR/CARU | 1830 | 78 | 26 | moderately dry |
| 6 | Five Mile Creek | PSME/CARU | 1220 | 213 | 22 | dry |
| 7 | Little Bear Burn | ABGR/CARU | 1520 | 224 | 15 | moderately dry |
| 8 | West Myrtle Creek | ABGR/CARU | 1830 | 355 | 13 | moderately dry |
| 9 | Anthony Burn | ABGR/CAGE | 1830 | 178 | 32 | moderately dry |
| 10 | Imnaha River Canyon | ABGR/VAME | 1280 | 164 | 2 | moist |
| 11 | Spaulding Gulch | ABGR/CARU | 1615 | 180 | 15 | moderately dry |
| 12 | Spring Mountain | PSME/CAGE | 1070 | 248 | 3 | moderately dry |
| 13 | Finley Sale Area | ABGR/SPBE | 1220 | 234 | 23 | moist |
| 14 | Troy | ABGR/SPBE | 1520 | 157 | 12 | moist |
| 15 | Smoothing Iron Ridge | ABGR/LIBO | 1520 | 113 | 6 | moist |

**Appendix B.** Age distribution, tree tally, basal area, and fire occurrences at each site.

Species codes: ABGR = *Abies grandis*
PIPO = *Pinus ponderosa*
PSME = *Pseudotsuga menziesii*
LAOC = *Larix occidentalis*
PICO = *Pinus contorta*

Fires are denoted on the age distributions with a small arrow (▾).

Estimated trees per hectare was calculated by multiplying the number of trees within tally plots by a factor based on the plot size. For instance, trees <3 m were tallied in a 10 m x 10 m plot (100 $m^2$); these tallies were multiplied by 100 to obtain an estimate of the number of trees per hectare (10,000 $m^2$).

Site 1

Establishment patterns: A large pulse of establishment occurred 80-90 years ago. Grand fir and Douglas-fir comprise 71% of the post-1900 establishment. Despite this large establishment pulse, ponderosa pine occupies 60% of the stand basal area and is the dominant canopy emergent (78% of trees >20 m). Douglas-fir dominates the mid-canopy layer (3 m - 20 m height), while grand fir and ponderosa pine densities in this layer are equal, but lower than Douglas-fir density.

Fire frequency: The MFRI at site 1 is 11.0 years. Fire return intervals range from a minimum of 4 years to a maximum of 37 years. The most recent fire recorded was in 1900.

Site 2

Establishment patterns: Grand fir and Douglas-fir show increased establishment beginning 110-120 years ago with peak establishment 90-100 years ago. Ponderosa pine establishment has been sparse in recent years, although it has been present at this site for at least 380 years. Ponderosa pine dominates the basal area (73% of total basal area) and accounts for 70% of trees >20 m in height. Douglas-fir and grand fir are the most prevalent trees in height classes <20 m, and account for 27% of the total basal area.

Fire frequency: The MFRI at site 2 is 15.7 years, with a range of 4 years to 53 years. Fire frequency decreased in 1900, although fires have occurred since then. The most recent fire occurred 45 years ago.

Site 3

Establishment patterns: Grand fir comprises 52% of the establishment since the last recorded fire, 49% of trees <20 m in height, and 19% of trees >20 m in height. Ponderosa pine dominates trees >20 m in height, but is also well represented in height classes <20 m. Ponderosa pine accounts for 45% of the total basal area. Douglas-fir is 50% of the total basal area and 24% of trees >20 m in height. Douglas-fir is poorly represented in height classes <20 m (4%).

Fire frequency: The MFRI at site 3 is 49.0 years. The minimum and maximum fire-free intervals are 42 years and 57 years, respectively. These frequencies have a narrow range, and seem consistently longer than frequencies at similar sites, but are well-represented on all scar samples from this site.

Site 4

Establishment patterns: Grand fir is the dominant tree <5 m in height (52%) and is 40% of trees 3-20 m in height. Approximately 27% of the basal area is grand fir. A pulse in grand fir establishment began 90-100 years ago. Ponderosa pine occupies 61% of the total basal area, 74% of the trees >20 m in height, and is also present in smaller amounts in height classes <20 m. Ponderosa pine establishment is represented throughout the range of age classes. Douglas-fir establishment peaked 80-90 years ago, but it occurs in all canopy layers (41% trees <3 m height, 45% trees 3-20 m height, 13% trees >20 m height) and comprises 12% of the total basal area. *Larix occidentalis* (western larch) is present in limited quantities.

Fire frequency: The MFRI at site 4 is 17.0 years, with a range for 7 years to 34 years. Fire frequency decreased 102-years ago, with one fire occurring since then in 1924.

Site 5

Establishment patterns: Grand fir dominates establishment since 1870 (52%) as well as in height classes <20 m (88%). It comprises 44% of the trees >20 m in height, and 48% of the total basal area. Ponderosa pine is represented in age classes >120 years, and is co-dominant with grand fir in the >20 m height class (44%). Douglas-fir began establishing at the same time as grand fir, and has been steady. Douglas-fir is a minor component of the overall basal area (5%), trees <20 m (11%), and trees >20 m (12%).

Fire frequency: The MFRI at site 5 is 43.2 years and is a very conservative estimate. The range is 9-119 years. It is very possible that fires between 1642 and 1761 occurred but either did not scar the sampled trees, or scars were obliterated by subsequent fires. This long interval nearly doubles the MFRI when calculated without the 119-year interval. The most recent fire was in 1901.

Site 6

Establishment patterns: A major pulse of Douglas-fir establishment occurred 80-110 years ago. Douglas-fir represents 63% of the total basal area in the plot, and dominates height classes <20 m (64%) and >20 m (82%). Ponderosa pine is present in a range of age classes, but no establishment peaks are noticeable. Ponderosa pine comprises 37% of the basal area, and is represented in height classes <20 m (36%) and >20 m (18%).

Fire frequency: The MFRI at site 6 is 9.9 years, with a range of 3 years to 20 years. Fire frequency appears to have been fairly constant from the late 1700s to the mid-1930s. The most recent fire recorded was in 1935.

Site 7

Establishment patterns: Grand fir establishment began in approximately 1900, with peak establishment 70-80 years ago. Grand fir is not represented in stand basal area samples, but is represented in height classes between 3 m and 20 m (26%) and >20 m (11%). Ponderosa pine establishment is steady, and peaked 90-100 years ago, but is not present in age classes younger than 70 years. Ponderosa pine comprises 84% of the total basal area, and 79% of the trees >20 m in height. Ponderosa pine occurs in <3 m height class, as well as 3 m-20 m height classes (67%). Douglas-fir is present in age classes <130 years. Douglas-fir accounts for 16% of the stand basal area, but only 7% of trees 3 m-20 m in height and 11% of trees >20 m.

Fire frequency: The MFRI at site 7 is 17.8 years. Return intervals vary from a minimum of 5 years to a maximum of 35 years. The most recent recorded fire was in 1902. Cessation of fires occurs simultaneously with grand fir establishment.

Site 8

Establishment patterns: Establishment in the past 100 years has been dominated by grand fir (83%) with minor contributions by ponderosa pine (11%) and Douglas-fir (6%). 80% of trees <20 m in height were grand fir, but only 13% of trees >20 m were grand fir. The basal area of grand fir is 15.4 $m^2$/ha (35% of total basal area). Ponderosa pine constitutes most of the establishment prior to 100 years ago (79%), has a basal area of 23.8 $m^2$/ha (55% of total basal area), and dominates the canopy emergents (>20 m in height; 74%). Douglas-fir is present, but is a minor component of trees <20 m (9%) and >20 m (13%) in height. Douglas-fir basal area is 4.2 $m^2$/ha, or about 10% of the total basal area.

Fire frequency: The MFRI at site 8 is 15.3 years. The range is from 5 years to 23 years. There have been no recorded fires since 1890. Note the pulse of grand fir establishment after fires ceased.

Site 9

Establishment patterns: Grand fir accounts for 68% of the trees <20 m in height. It was not present in sample plots for the height class >20 m. Basal area for grand fir was 2.8 $m^2$/ha (7% of total basal area). Age classes older than 100 are dominated by ponderosa pine. Ponderosa pine has a basal area of 30.8 $m^2$/ha (73% of total basal area) and was only recorded in the height class >20 m (88%). Douglas-fir establishment began 110-120 years ago and is represented in height classes <20 m (32%) and >20 m (12%). The basal area for Douglas-fir is 8.4 $m^2$/ha (20% of total basal area).

Fire frequency: The MFRI at site 9 is 16.0 years, however, only two intervals (4 years and 28 years) were used to calculate this mean. The most recent recorded fire was 114 years ago (1878). Note that grand fir establishment increased during the decade following the most recent fire.

Site 10

Establishment patterns: The age distribution on this plot was very narrow. All sampled trees were younger than 120 years, although scar sections were taken from trees older than 120 years. Despite this narrow age range, establishment patterns are still apparent. Shade-tolerant grand fir has had a recent pulse of establishment, which may correspond to canopy closure of the older ponderosa pine and Douglas-fir. Grand fir dominates height classes <20 m (78%) and is also a component of the overstory (>20 m in height; 5%). Basal area for grand fir is 4.2 $m^2$/ha (8% of total basal area). Ponderosa pine and Douglas-fir comprises most of the establishment prior to 50 years ago, although ponderosa pine clearly dominates the overstory (>20 m in height; 82%) and in basal area (40.6 $m^2$/ha; 76% of total basal area). Douglas-fir is

13% of trees >20 m in height, and 20% of trees <20 m in height. The basal area for Douglas-fir is 8.4 $m^2$/ha (16% of total basal area).

Fire frequency: The MFRI at site 10 is 9.9 years. The minimum fire-free interval is 2 years, and the maximum is 29 years. Recorded fires were frequent until 1914, which corresponds to the beginning of grand fir establishment.

<u>Site 11</u>

Establishment patterns: Grand fir shows a clear trend of establishment beginning 160-170 years ago and peaking 60-70 years ago. 31% of trees <20 m in height are grand fir, 7% of trees >20 m in height are grand fir, and 23% (7.0 $m^2$/ha) of the total basal area is grand fir. Ponderosa pine establishment is sporadic and low. Ponderosa pine is present in the lower canopy (<20 m in height; 35%) and dominates in the height class >20 m (64%). The basal area for ponderosa pine is 15.4 $m^2$/ha (50% of total basal area). Douglas-fir shows a slight establishment pattern beginning 110-120 years ago and peaking 60-70 years ago. Douglas-fir accounts for 33% of trees <20 m in height, and 29% of those >20 m in height. The basal area for Douglas-fir is 8.4 $m^2$/ha.

Fire frequency: The MFRI at site 11 is 24.0 years. The range of fire-free intervals is 16 years to 48 years. The most recent recorded fire was in 1919.

<u>Site 12</u>

Establishment patterns: Similar to site 10, this site has a very narrow age range represented. Grand fir, ponderosa pine, and Douglas-fir are evenly represented in the age class distribution (30%, 42%, and 26%, respectively). Pulses in establishment for all three species and western larch occurred 100-120 years ago. Grand fir is 77% of trees <20 m in height, and 17% of those >20 m in height. 5% of the total basal area is grand fir (2.8 $m^2$/ha). Ponderosa pine is present in height classes <20 m (19%), dominates in trees >20 m in height (51%), and has a basal area of 26.6 $m^2$/ha (51% of total basal area). Douglas-fir is present in minor amounts in trees <20 m in height, but comprises 30% of trees >20 m in height, and 38% of the total basal area. The basal area of the single sampled western larch was equal to that of grand fir at this site (2.8 $m^2$/ha).

Fire frequency: The MFRI is 30.8 years at site 12. The range is from 14 years to 68 years, with the most recent fire event in 1977. Because this site has been entered and selectively harvested, it is quite possible that this fire (1977) was part of a harvest operation. The fire previous to the 1977 event was in 1909. Also of note is that the Whitman Trail is in the vicinity of this site, which may account for the lack trees older than 120 years.

<u>Site 13</u>

Establishment patterns: A prominent pulse of grand fir establishment occurred 120-130 years ago and peaked 90-110 years ago. Grand fir accounts for 93% of the establishment of sampled trees since 1862. 96% of trees <20 m in height are grand fir, while 86% of trees >20 m in height are grand fir. The basal area for grand fir is 29.4 $m^2$/ha (58% of total basal area). Ponderosa pine is represented by several trees older than 130 years. Ponderosa pine constitutes 36% of the total basal area, but only 12% of the trees >20 m. Douglas-fir and western larch are present, but only Douglas-fir is represented in the age distribution. Both Douglas-fir and western larch have a basal area of 1.4 $m^2$/ha (3% of total basal area).

Fire frequency: The MFRI at site 13 is 24.8 years. The minimum fire-free interval is 9 years, and the maximum is 39 years. The most recent fire recorded was in 1900.

Site 14

Establishment patterns: Most grand fir establishment has occurred within the past 110 years with a peak in establishment 90-100 years ago. Grand fir dominates all height classes (<20 m = 73%, >20 m = 59%) and equals ponderosa pine in basal area (15.4 $m^2$/ha; 41% of total basal area). Ponderosa pine constitutes 82% of the establishment prior to 110 years ago. 20% of trees <20 m in height, and 23% of trees >20 m in height are ponderosa pine. Douglas-fir has a similar establishment pattern to grand fir, but there are fewer individuals. Douglas-fir is 2% of trees <20 m in height, and 14% of trees >20 m in height. The basal area for Douglas-fir is 2.8 $m^2$/ha (7% of total basal area). Western larch is not represented in the age distribution, but constitutes 4% of trees <20 m in height and 5% of trees >20 m in height. Western larch has a basal area of 4.4 $m^2$/ha (12% of total basal area).

Fire frequency: The MFRI for site 14 is 19.4 years. The minimum fire-free interval is 5 years, and the maximum is 36 years. The most recent fire occurred in 1941.

Site 15

Establishment patterns: Grand fir establishment dominated the period between 70 and 150 years ago, with a peak 90-100 years ago. It comprises 69% of trees <20 m in height, 19% of trees >20 m in height, and has a basal area of 16.8 $m^2$/ha (32% of total basal area). Ponderosa pine is present in the oldest and youngest age classes. Ponderosa pine is 59% of trees >20 m in height, and has a basal area of 33.6 $m^2$/ha. No ponderosa pine was present in the tree tallies for heights <20 m. Douglas-fir and western larch have similar periods of sparse establishment. Both are present in height classes <20 m and >20 m, although Douglas-fir is more abundant in <20 m height classes than western larch (28% and 7%, respectively), while western larch is slightly more abundant than Douglas-fir in the >20 m height class (13% and 9%, respectively). Douglas-fir and western larch have the same basal area (1.4 $m^2$/ha; 3% of total basal area).

Fire frequency: The MFRI at site 15 is 10.6 years with a range of 3 years to 29 years. Fire return intervals were <25 years, with most <15 years, until 1880. The long fire-free interval between 1880 and 1909 may have allowed the pulse of grand fir to establish 90-100 years ago. The most recent recorded fire was in 1920.

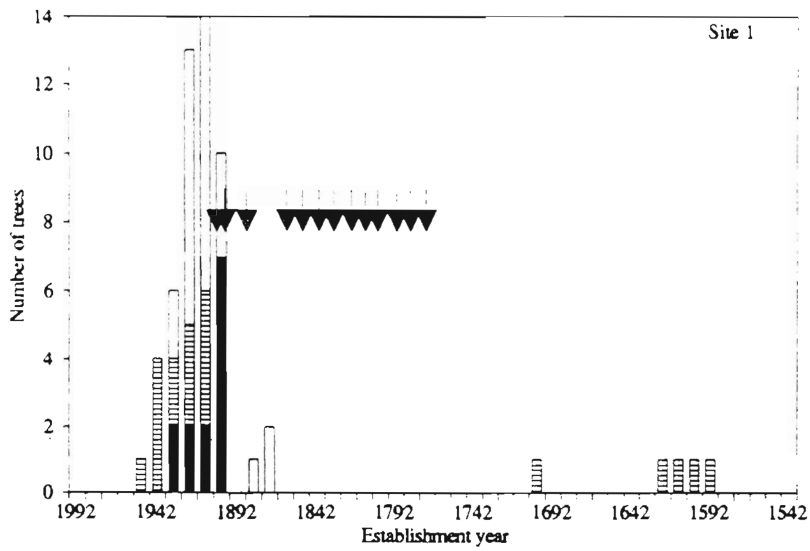


Figure B1. Age distribution by species at site 1.

ABGR PIPO PSME

Table B1. Tree tally and basal area data at site 1.

| Species | height class (m) | number of trees in tally | trees/ha | basal area (m2/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 0 | 0 | 5.6 |
| | 3-10 m | 3 | 75 | |
| | 10 -20 m | 5 | 125 | |
| | 20+m | 0 | 0 | |
| PIPO | 0-3 m | 10 | 1000 | 19.6 |
| | 3-10 m | 14 | 350 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 7 | 43.75 | |
| PSME | 0-3 m | 1 | 100 | 12.6 |
| | 3-10 m | 24 | 600 | |
| | 10-20 m | 17 | 425 | |
| | 20+m | 2 | 12.5 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

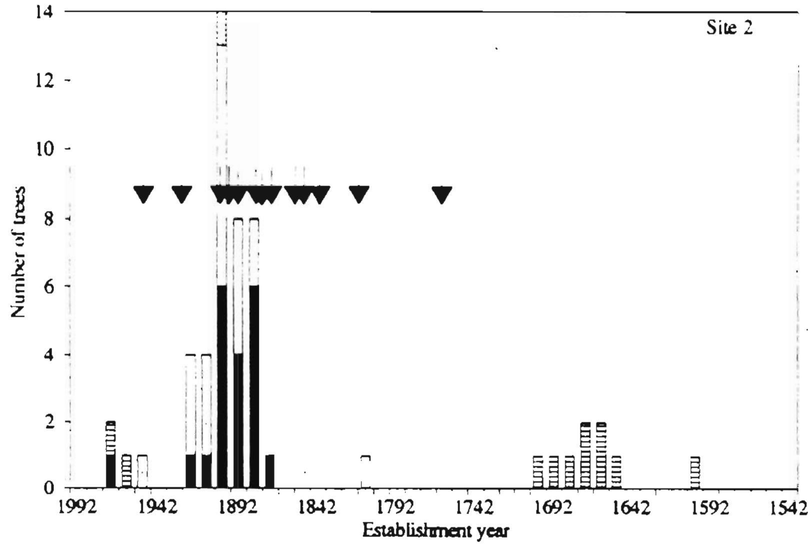


Figure B2. Age distribution by species at site 2.

ABGR PIPO PSME LAOC

Table B2. Tree tally and basal area data at site 2.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 10 | 1000 | 2.8 |
| | 3-10 m | 10 | 250 | |
| | 10-20 m | 4 | 100 | |
| | 20+m | 1 | 6.25 | |
| PIPO | 0-3 m | 0 | 0 | 30.8 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 16 | 100 | |
| PSME | 0-3 m | 11 | 1100 | 8.4 |
| | 3-10 m | 26 | 650 | |
| | 10-20 m | 3 | 75 | |
| | 20+m | 5 | 31.25 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 2 | 12.5 | |

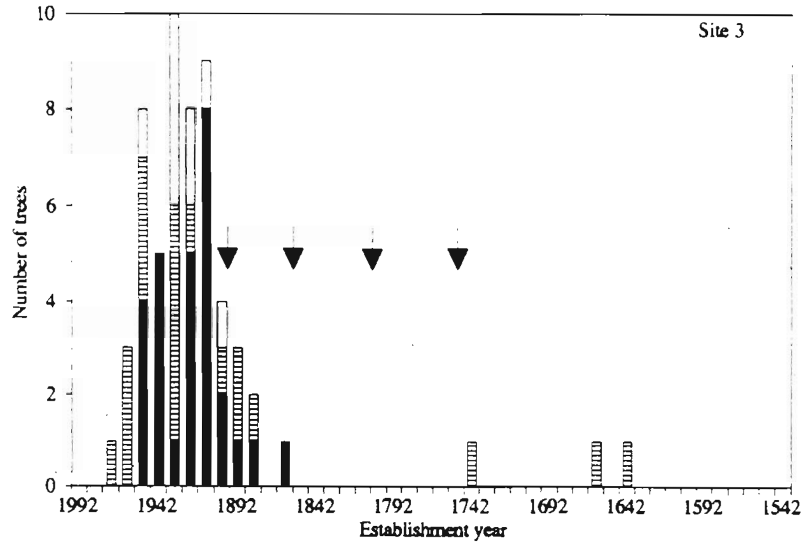


Figure B3. Age distribution by species at site 3.

ABGR PIPO PSME

Table B3. Tree tally and basal area data at site 3.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 8 | 800 | 1.4 |
| | 3-10 m | 5 | 125 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 4 | 25 | |
| PIPO | 0-3 m | 6 | 600 | 12.6 |
| | 3-10 m | 6 | 150 | |
| | 10-20 m | 6 | 150 | |
| | 20+m | 11 | 68.75 | |
| PSME | 0-3 m | 0 | 0 | 14.0 |
| | 3-10 m | 3 | 75 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 5 | 31.25 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

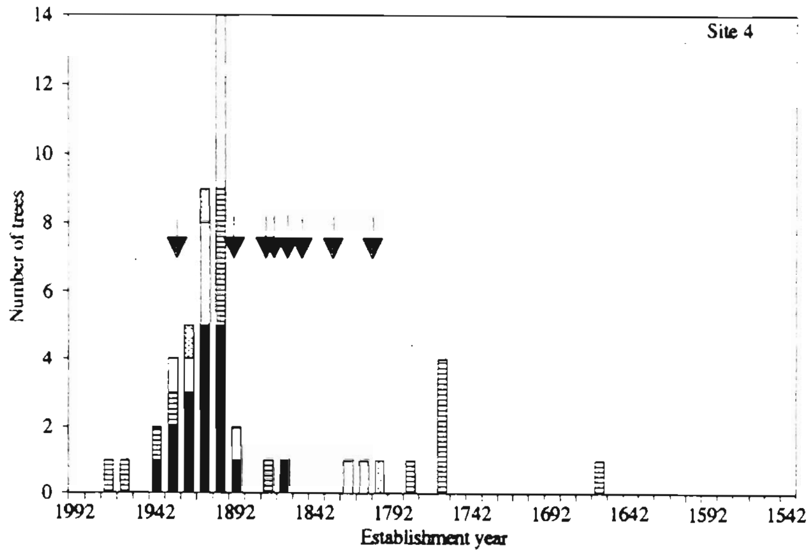


Figure B4. Age distribution by species at site 4.

ABGR PIPO PSME LAOC

Table B4. Tree tally and basal area data at site 4.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 14 | 1400 | 12.6 |
| | 3-10 m | 14 | 350 | |
| | 10-20 m | 8 | 200 | |
| | 20+m | 0 | 0 | |
| PIPO | 0-3 m | 2 | 200 | 28.0 |
| | 3-10 m | 2 | 50 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 17 | 106.25 | |
| PSME | 0-3 m | 11 | 1100 | 5.6 |
| | 3-10 m | 22 | 550 | |
| | 10-20 m | 3 | 75 | |
| | 20+m | 3 | 18.75 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 6 | 150 | |
| | 20+m | 3 | 18.75 | |

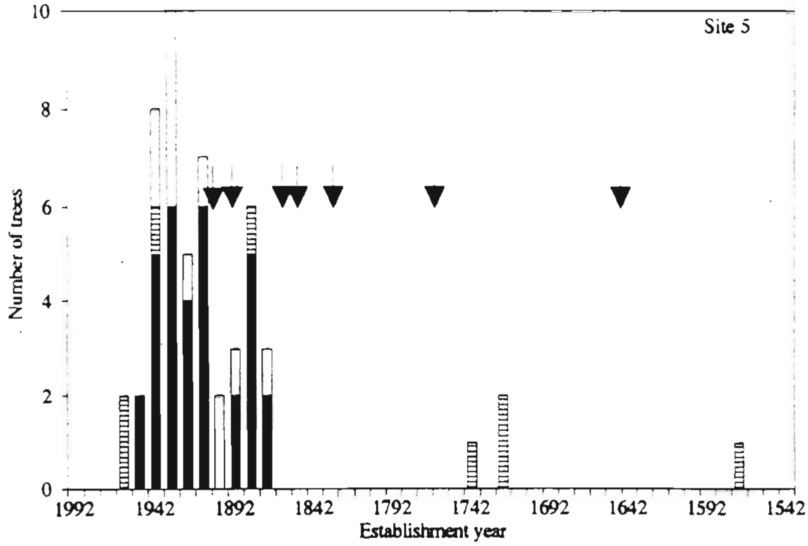


Figure B5. Age distribution by species at site 5.

ABGR PIPO PSME

Table B5. Tree tally and basal area data at site 5.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 6 | 600 | 14.0 |
| | 3-10 m | 10 | 250 | |
| | 10-20 m | 6 | 150 | |
| | 20+m | 7 | 43.75 | |
| PIPO | 0-3 m | 0 | 0 | 14.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 7 | 43.75 | |
| PSME | 0-3 m | 0 | 0 | 1.4 |
| | 3-10 m | 5 | 125 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 2 | 12.5 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 1 | 25 | |
| | 20+m | 0 | 0 | |

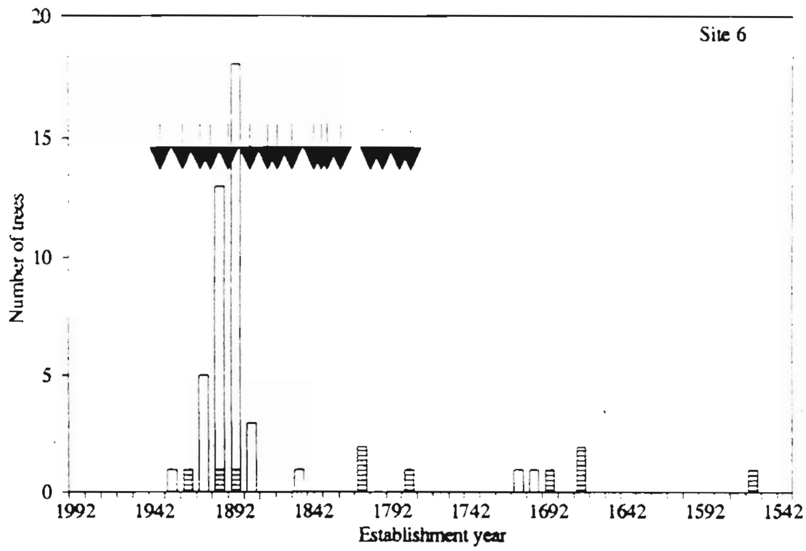


Figure B6. Age distribution by species at site 6.



Table B6. Tree tally and basal area data at site 6.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |
| PIPO | 0-3 m | 0 | 0 | 18.2 |
| | 3-10 m | 7 | 175 | |
| | 10-20 m | 2 | 50 | |
| | 20+m | 8 | 50 | |
| PSME | 0-3 m | 0 | 0 | 30.8 |
| | 3-10 m | 11 | 275 | |
| | 10-20 m | 5 | 125 | |
| | 20+m | 37 | 231.25 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

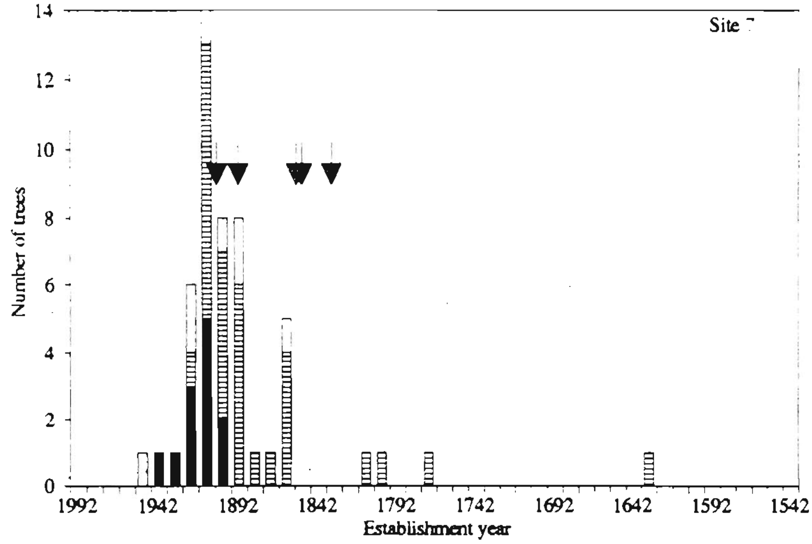


Figure B7. Age distribution by species at site 7.

ABGR PIPO PSME

Table B7. Tree tally and basal area data at site 7.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 5 | 125 | |
| | 10-20 m | 2 | 50 | |
| | 20+m | 3 | 18.75 | |
| PIPO | 0-3 m | 2 | 200 | 50.4 |
| | 3-10 m | 17 | 425 | |
| | 10-20 m | 1 | 25 | |
| | 20+m | 22 | 137.50 | |
| PSME | 0-3 m | 0 | 0 | 9.8 |
| | 3-10 m | 2 | 50 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 3 | 18.75 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

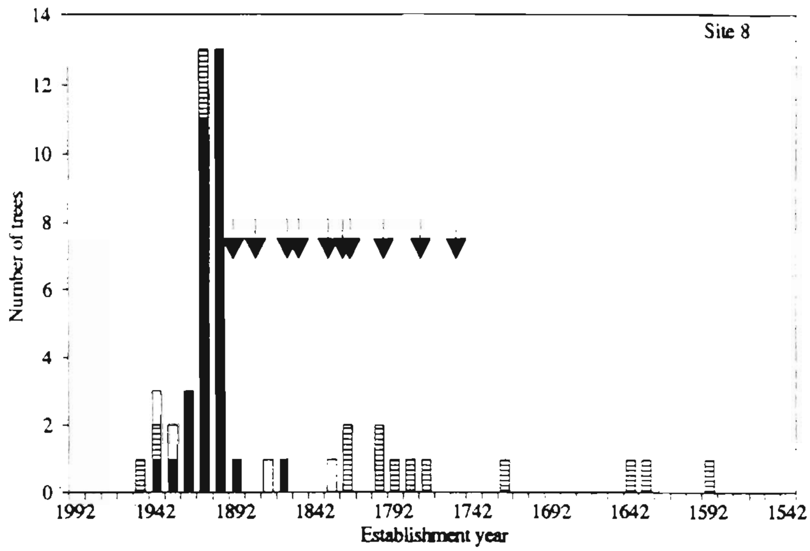


Figure B8. Age distribution by species at site 8.

Table B8. Tree tally and basal area data at site 8.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 7 | 700 | 15.4 |
| | 3-10 m | 46 | 1150 | |
| | 10-20 m | 12 | 300 | |
| | 20+m | 3 | 18.75 | |
| PIPO | 0-3 m | 3 | 300 | 23.8 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 17 | 106.25 | |
| PSME | 0-3 m | 1 | 100 | 4.2 |
| | 3-10 m | 5 | 125 | |
| | 10-20 m | 1 | 25 | |
| | 20+m | 3 | 18.75 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

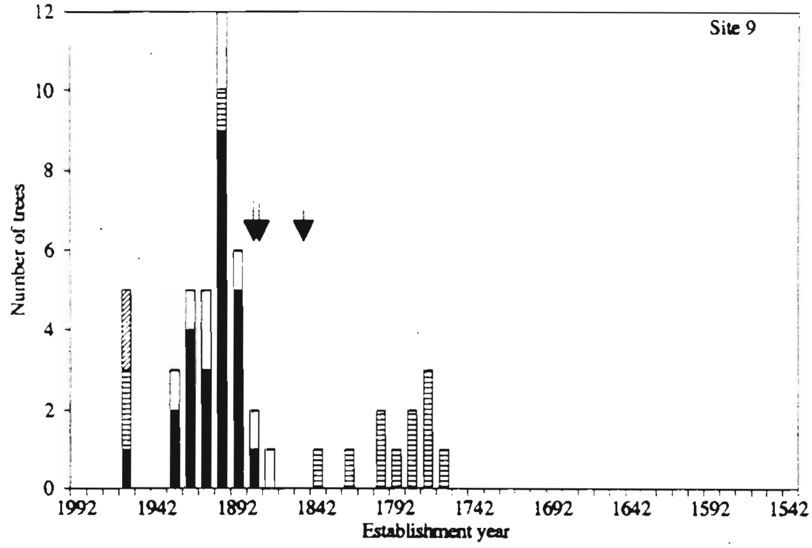


Figure B9. Age distribution by species at site 9.

ABGR PIPO PSME PICO

Table B9. Tree tally and basal area data at site 9.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 6 | 600 | 2.8 |
| | 3-10 m | 19 | 475 | |
| | 10-20 m | 7 | 175 | |
| | 20+m | 0 | 0 | |
| PIPO | 0-3 m | 0 | 0 | 30.8 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 23 | 143.75 | |
| PSME | 0-3 m | 4 | 400 | 8.4 |
| | 3-10 m | 8 | 200 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 3 | 18.75 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

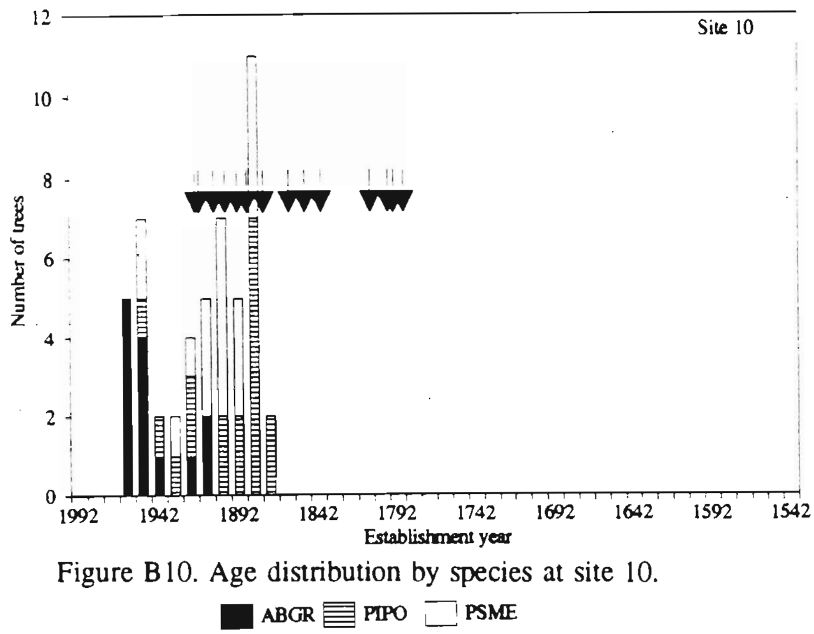


Figure B10. Age distribution by species at site 10.

Table B10. Tree tally and basal area data at site 10.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 8 | 800 | 4.2 |
| | 3-10 m | 8 | 200 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 2 | 12.5 | |
| PIPO | 0-3 m | 0 | 0 | 40.6 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 1 | 25 | |
| | 20+m | 33 | 206.5 | |
| PSME | 0-3 m | 1 | 100 | 8.4 |
| | 3-10 m | 6 | 150 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 5 | 31.25 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

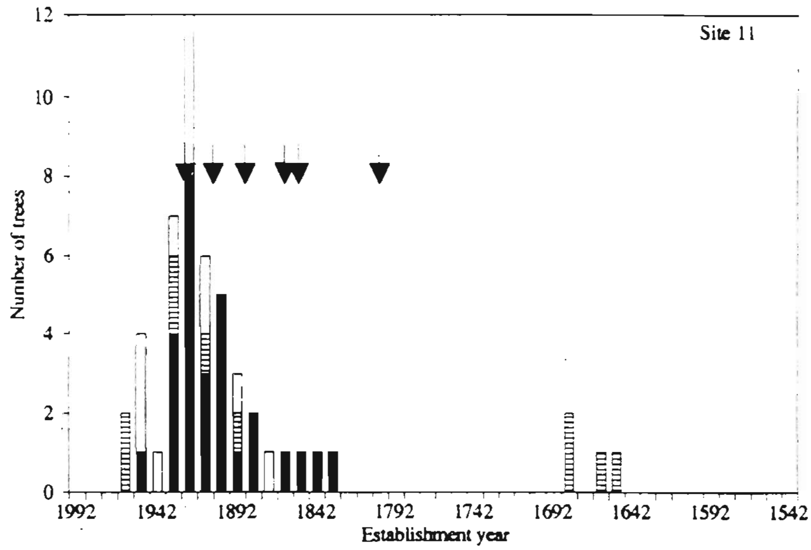


Figure B11. Age distribution by species at site 11.

Table B11. Tree tally and basal area data at site 11.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 3 | 300 | 7.0 |
| | 3-10 m | 4 | 100 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 1 | 6.25 | |
| PIPO | 0-3 m | 4 | 400 | 15.4 |
| | 3-10 m | 2 | 50 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 9 | 56.25 | |
| PSME | 0-3 m | 3 | 300 | 8.4 |
| | 3-10 m | 3 | 75 | |
| | 10-20 m | 2 | 50 | |
| | 20+m | 4 | 25 | |
| LAOC | 0-3 m | 0 | 0 | 0.0 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |

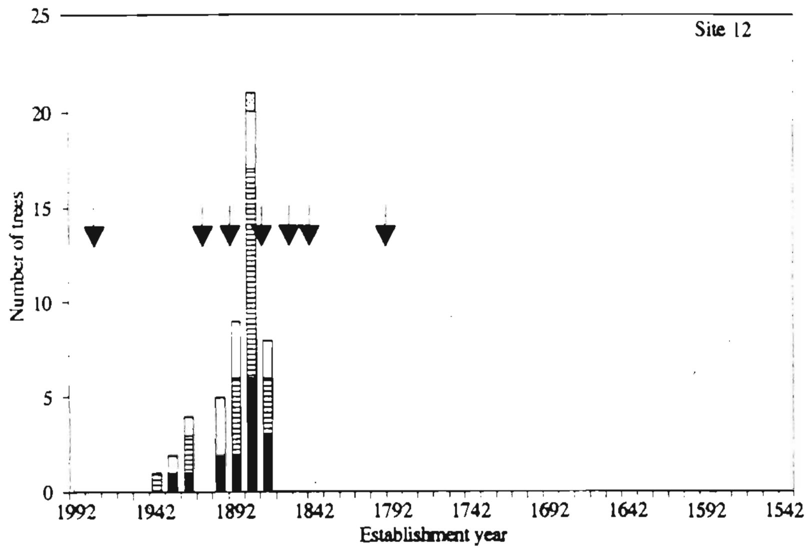


Figure B12. Age distribution by species at site 12.

Table B12. Tree tally and basal area data at site 12.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 5 | 500 | 2.8 |
| | 3-10 m | 1 | 25 | |
| | 10-20 m | 3 | 75 | |
| | 20+m | 8 | 50 | |
| PIPO | 0-3 m | 0 | 0 | 26.6 |
| | 3-10 m | 6 | 150 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 24 | 150 | |
| PSME | 0-3 m | 0 | 0 | 19.6 |
| | 3-10 m | 1 | 25 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 14 | 87.5 | |
| LAOC | 0-3 m | 0 | 0 | 2.8 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 1 | 6.25 | |

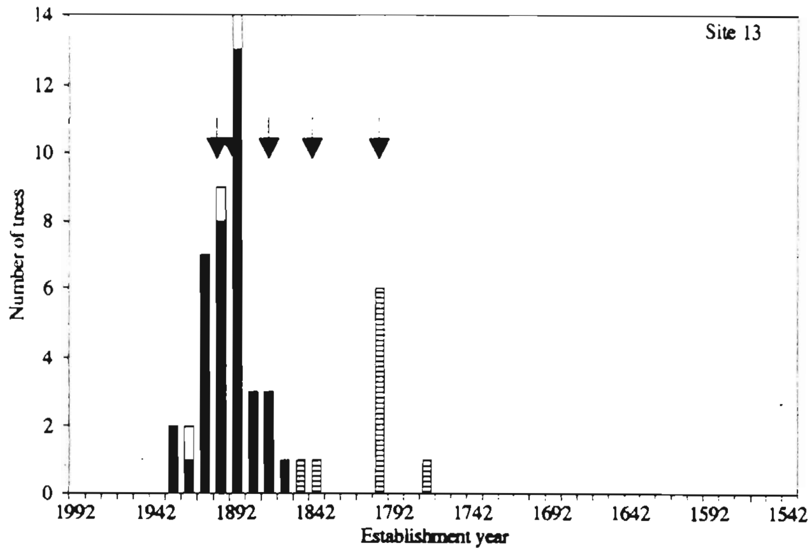


Figure B13. Age distribution by species at site 13.



Table B13. Tree tally and basal area data at site 13.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 1 | 100 | 29.4 |
| | 3-10 m | 10 | 250 | |
| | 10-20 m | 9 | 225 | |
| | 20+m | 74 | 462.5 | |
| PIPO | 0-3 m | 0 | 0 | 18.2 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 1 | 25 | |
| | 20+m | 10 | 62.5 | |
| PSME | 0-3 m | 0 | 0 | 1.4 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 0 | 0 | |
| LAOC | 0-3 m | 0 | 0 | 1.4 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 2 | 12.5 | |

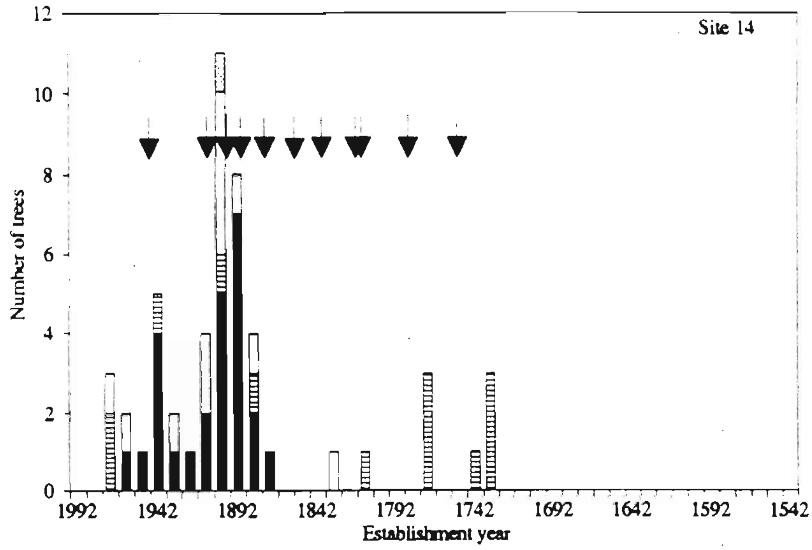


Figure B14. Age distribution by species at site 14.

ABGR PIPO PSME LAOC

Table B14. Tree tally and basal area data at site 14.

| Species | height class (m) | number of trees in tally | trees/ha | basal area ($m^2$/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 5 | 500 | 15.4 |
| | 3-10 m | 13 | 325 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 13 | 81.25 | |
| PIPO | 0-3 m | 2 | 200 | 15.4 |
| | 3-10 m | 1 | 25 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 5 | 31.25 | |
| PSME | 0-3 m | 0 | 0 | 2.8 |
| | 3-10 m | 1 | 25 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 3 | 18.75 | |
| LAOC | 0-3 m | 0 | 0 | 4.2 |
| | 3-10 m | 2 | 50 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 1 | 6.25 | |

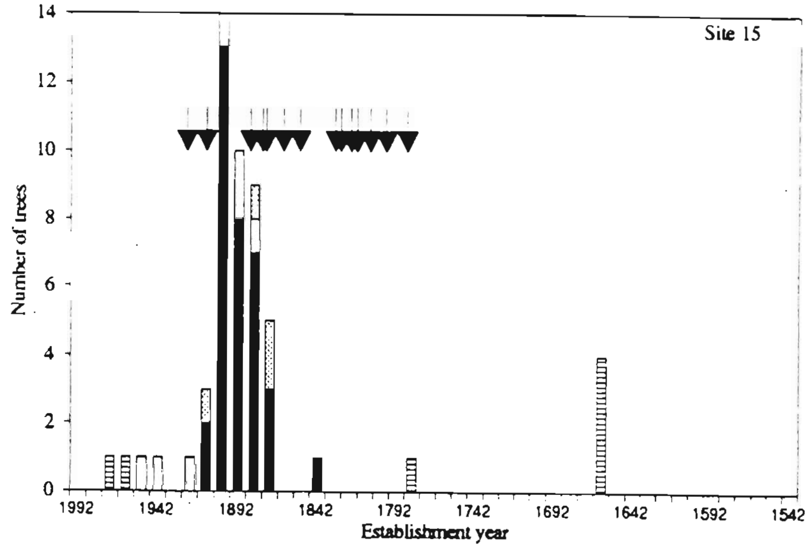


Figure B15. Age distribution by species at site 15.

ABGR PIPO PSME LAOC

Table B15. Tree tally and basal area data at site 15.

| Species | height class (m) | number of trees in tally | trees/ha | basal area (m²/ha) |
|---|---|---|---|---|
| ABGR | 0-3 m | 2 | 200 | 16.8 |
| | 3-10 m | 20 | 500 | |
| | 10-20 m | 15 | 375 | |
| | 20+m | 6 | 37.5 | |
| PIPO | 0-3 m | 0 | 0 | 33.6 |
| | 3-10 m | 0 | 0 | |
| | 10-20 m | 0 | 0 | |
| | 20+m | 19 | 118.75 | |
| PSME | 0-3 m | 0 | 0 | 1.4 |
| | 3-10 m | 4 | 100 | |
| | 10-20 m | 11 | 275 | |
| | 20+m | 3 | 18.75 | |
| LAOC | 0-3 m | 0 | 0 | 1.4 |
| | 3-10 m | 1 | 25 | |
| | 10-20 m | 3 | 75 | |
| | 20+m | 4 | 25 | |

**Appendix C.** Statistical tests and results.

Non-parametric squared ranks test for equal variances (Conover 1980)

Data used in this test:

From each observation, subtract the sample mean, and convert the sign of the resulting difference to +. Rank the combined absolute differences from smallest to largest, assigning average ranks in case of ties. Compute the sum of squares of the ranks for each sample, letting $S_1$, $S_2$, ..., $S_k$ denote the sums for each of the $k$ samples.

$H_o$: All $k$ populations are identical, except for possibly different means
$H_1$: Some of the population variances are not equal to each other

Test statistic:

$$T = \frac{1}{D^2}\left[\sum_{j=1}^{k} \frac{S_j^2}{n_j} - N(S_{avg})^2\right]$$

where $n_j$ = number of observations (intervals) in sample $j$
$N = n_1 + n_2 + n_3 + \ldots + n_j$
$S_j$ = the sum of squared ranks in sample $j$
$S_{avg}$ = the average of all the squared ranks = $1/N\ [\ \sum S_j\ ]$, where $j = 1$ to $k$
$D^2 = [1/(N-1)][\ \sum R_i^4 - N(S_{avg})^2\ ]$, where $i = 1$ to N

Reject $H_o$ if T exceeds the $1 - \alpha$ quantile of the chi-square distribution with $k - 1$ degrees of freedom.

$T = |-295.55|$ and $t_{0.05,(2),107} = 1.983$

since $|-295.55| > 1.983 \therefore$ reject $H_o$

Non-parametric comparisons with unequal sample sizes (Zar 1984)

Data used in this test:

Data are ranked as described above, and rank sums computed for each site. The mean ranks are arranged in order of increasing magnitude. The conclusions reached by multiple comparison testing are dependent upon the order in which the pairwise comparisons are considered. Pairwise differences between rank sums are tabulated starting with the difference between the largest and smallest rank sums, then comparing the largest to the next smallest, and so on until the largest has been compared with the second largest. Then, the second largest is compared with the smallest, the second largest with the second smallest, and so on. If no significant difference exists between elements in a pair ($H_o$ is not rejected), it is concluded that no difference exists between any means enclosed by these two, and such differences are not tested for.

$H_o$: fire return interval length is the same at every site
$H_1$: fire return interval length is not the same at every site

Test statistic:

$$Q = (R_{avg\ B} - R_{avg\ A}) / SE$$

where: $R_{avg\ B} = R_B - n_B$

$n_B$ = number of observations (intervals) in sample B

$\sum T = \sum (t^3 - t_i)$ where $t_i$ is the number of ties in the $i^{th}$ group, and $m$ is the number of groups of tied ranks

$N = n_1 + n_2 + n_3 + \ldots + n_j$

$$SE = \sqrt{\left(\frac{N(N+1)}{12} - \frac{\sum_{i=1}^{n} T}{12(N+1)}\right)\left(\frac{1}{n_a} + \frac{1}{n_b}\right)}$$

Reject $H_o$ if $Q > Q_{\alpha,k}$ where $Q_{\alpha,k}$ is defined in Table B.14 in Zar (1984).

$Q_{0.05,(2),15} = 3.494$

Resulting groups of sites at $\alpha = 0.05$:

5
12
9, 2, 11, 14, 13, 4, 7, 3, 8
15
1
6
10

**Appendix D.** Litter and duff measurements.

Litter, and litter and duff measurements (cm) at ten random points throughout each plot at every site. Litter ("L") was measured from the upper surface of any dead and downed woody material to the litter/duff interface. Litter and duff ("LD") measurements were taken from the upper surface of the litter to the duff/mineral soil interface. Average litter (AVG LIT) and litter and duff (AVG L + D) measurements were calculated for each plot.

Table D1. Litter (L) and litter and duff (L+D) measurements at each study plot (cm).

| SITE | PLOT | L1 | LD1 | L2 | LD2 | L3 | LD3 | L4 | LD4 | L5 | LD5 | L6 | LD6 | L7 | LD7 | L8 | LD8 | L9 | LD9 | L10 | LD10 | AVG LITT | AVG L+D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.8 | 4.3 | 1.0 | 4.2 | 0.6 | 0.8 | 0.3 | 3.4 | 0.4 | 5.7 | 0.6 | 1.3 | 0.5 | 6.5 | 0.4 | 3.2 | 0.8 | 1.9 | 1.2 | 2.0 | 0.66 | 3.33 |
| 1 | 2 | 0.3 | 0.5 | 0.2 | 0.2 | 0.3 | 0.4 | 0.1 | 0.3 | 0.4 | 0.9 | 0.3 | 0.5 | 0.4 | 0.6 | 0.5 | 1.2 | 0.3 | 0.5 | 0.2 | 0.4 | 0.3 | 0.55 |
| 1 | 3 | 0.4 | 0.6 | 1.1 | 1.6 | 0.9 | 1.6 | 0.9 | 1.3 | 1.1 | 3.0 | 1.2 | 2.9 | 1.0 | 2.0 | 0.5 | 2.3 | 0.4 | 1.6 | 0.8 | 2.3 | 0.83 | 1.92 |
| 2 | 1 | 4.0 | 4.5 | 0.8 | 7.5 | 0.9 | 2.1 | 1.1 | 1.3 | 1.1 | 5.7 | 2.0 | 2.5 | 1.7 | 3.1 | 1.6 | 4.0 | 3.2 | 5.4 | 2.0 | 5.5 | 1.84 | 4.16 |
| 2 | 2 | 0.6 | 1.2 | 0.9 | 2.2 | 0.3 | 2.4 | 0.3 | 1.1 | 0.4 | 1.4 | 0.2 | 2.7 | 0.3 | 1.7 | 0.3 | 3.4 | 0.5 | 2.1 | 0.8 | 1.5 | 0.46 | 1.97 |
| 2 | 3 | 0.1 | 0.3 | 0.6 | 2.8 | 1.4 | 2.9 | 0.6 | 3.3 | 0.4 | 1.9 | 1.0 | 4.2 | 1.3 | 2.0 | 0.2 | 0.5 | 0.3 | 1.2 | 0.6 | 0.6 | 0.65 | 1.97 |
| 3 | 1 | 3.0 | 6.0 | 1.3 | 1.3 | 1.4 | 1.6 | 0.2 | 0.2 | 0.1 | 0.4 | 0.7 | 2.9 | 1.2 | 2.3 | 0.8 | 2.5 | 2.3 | 2.7 | 2.2 | 3.1 | 1.32 | 2.3 |
| 3 | 2 | 0.6 | 0.6 | 0.0 | 6.5 | 0.6 | 1.0 | 0.2 | 0.3 | 1.2 | 3.4 | 0.2 | 0.8 | 1.2 | 1.2 | 1.6 | 1.8 | 2.4 | 3.3 | 2.2 | 2.4 | 1.02 | 2.13 |
| 3 | 3 | 0.8 | 2.4 | 1.1 | 1.1 | 0.6 | 3.3 | 1.0 | 4.0 | 1.4 | 2.3 | 1.3 | 1.5 | 1.0 | 1.2 | 0.8 | 0.9 | 1.0 | 1.2 | 0.9 | 1.1 | 0.99 | 1.9 |
| 4 | 1 | 1.0 | 2.2 | 1.3 | 4.2 | 0.4 | 1.0 | 0.8 | 1.3 | 0.6 | 1.4 | 0.4 | 1.2 | 0.8 | 2.1 | 1.3 | 4.5 | 0.6 | 1.7 | 0.4 | 0.4 | 0.76 | 2 |
| 4 | 2 | 0.8 | 5.3 | 0.6 | 1.4 | 0.3 | 4.4 | 0.8 | 1.9 | 0.3 | 1.2 | 0.2 | 1.3 | 0.2 | 3.7 | 1.0 | 4.5 | 1.2 | 3.7 | 0.2 | 0.4 | 0.56 | 2.78 |
| 4 | 3 | 0.5 | 2.5 | 0.2 | 1.0 | 3.5 | 7.0 | 1.0 | 2.0 | 0.4 | 1.4 | 2.0 | 5.0 | 1.5 | 3.0 | 0.3 | 1.0 | 1.0 | 1.5 | 1.0 | 2.4 | 1.14 | 2.68 |
| 5 | 1 | 0.4 | 6.2 | 1.2 | 3.0 | 0.6 | 3.8 | 0.8 | 0.8 | 0.6 | 4.2 | 0.8 | 5.2 | 1.2 | 6.0 | 0.3 | 6.2 | 0.4 | 4.1 | 0.7 | 3.0 | 0.7 | 4.25 |
| 5 | 2 | 0.5 | 3.2 | 1.1 | 1.9 | 0.3 | 0.3 | 0.2 | 0.3 | 0.6 | 0.8 | 0.6 | 3.2 | 1.3 | 1.5 | 0.8 | 6.1 | 1.3 | 2.1 | 0.2 | 2.4 | 0.69 | 2.18 |
| 5 | 3 | 1.3 | 2.4 | 0.6 | 1.2 | 1.3 | 4.2 | 0.8 | 1.5 | 0.2 | 1.3 | 0.4 | 2.7 | 0.8 | 1.3 | 0.3 | 4.5 | 0.4 | 1.9 | 1.5 | 2.1 | 0.76 | 2.31 |
| 6 | 1 | 0.4 | 7.3 | 0.8 | 1.3 | 0.3 | 2.7 | 0.3 | 0.8 | 0.2 | 1.2 | 1.8 | 6.0 | 2.0 | 4.3 | 0.3 | 0.8 | 0.8 | 2.3 | 1.4 | 5.0 | 0.83 | 3.17 |
| 6 | 2 | 0.3 | 0.5 | 0.3 | 1.2 | 0.3 | 1.3 | 0.6 | 2.1 | 0.8 | 4.9 | 0.2 | 0.6 | 0.8 | 2.7 | 0.3 | 0.4 | 0.2 | 2.0 | 0.3 | 3.7 | 0.41 | 1.94 |
| 6 | 3 | 0.3 | 4.8 | 0.3 | 0.5 | 1.4 | 3.8 | 0.2 | 1.8 | 0.2 | 0.3 | 0.6 | 2.3 | 1.0 | 1.2 | 1.2 | 3.7 | 0.3 | 2.0 | 0.7 | 2.9 | 0.62 | 2.33 |
| 7 | 1 | 2.0 | 2.7 | 1.0 | 5.2 | 1.2 | 4.2 | 1.0 | 3.1 | 1.0 | 1.8 | 1.0 | 2.9 | 0.6 | 1.6 | 1.3 | 3.3 | 1.7 | 5.3 | 2.0 | 7.2 | 1.28 | 3.73 |
| 7 | 2 | 0.2 | 1.0 | 0.2 | 1.3 | 0.5 | 2.3 | 1.0 | 3.1 | 1.3 | 3.9 | 1.3 | 2.1 | 1.3 | 3.6 | 0.2 | 0.2 | 0.2 | 0.9 | 0.6 | 2.1 | 0.68 | 2.05 |
| 7 | 3 | 0.8 | 10.4 | 0.4 | 2.1 | 1.2 | 8.2 | 0.4 | 2.8 | 0.5 | 2.6 | 1.2 | 4.3 | 1.1 | 4.2 | 0.3 | 1.2 | 1.2 | 1.5 | 0.8 | 2.3 | 0.79 | 3.96 |
| 8 | 1 | 0.8 | 1.6 | 0.4 | 1.6 | 0.6 | 1.7 | 1.4 | 2.5 | 1.8 | 3.8 | 2.3 | 3.0 | 3.0 | 3.6 | 2.9 | 4.5 | 3.4 | 4.2 | 1.7 | 2.6 | 1.83 | 2.91 |
| 8 | 2 | 0.4 | 0.4 | 0.7 | 4.3 | 1.4 | 2.3 | 0.4 | 1.2 | 0.3 | 3.1 | 0.5 | 2.6 | 0.3 | 1.8 | 1.0 | 3.3 | 0.6 | 2.2 | 0.4 | 2.0 | 0.6 | 2.32 |
| 8 | 3 | 0.4 | 2.1 | 0.6 | 1.3 | 0.4 | 0.4 | 1.0 | 2.1 | 1.1 | 10.4 | 0.9 | 7.0 | 0.7 | 0.9 | 0.8 | 3.1 | 0.7 | 3.2 | 0.3 | 1.1 | 0.69 | 3.16 |
| 9 | 1 | 0.2 | 1.9 | 1.3 | 13.0 | 0.9 | 1.2 | 0.6 | 3.9 | 2.6 | 4.5 | 1.6 | 5.2 | 1.2 | 2.8 | 2.8 | 12.0 | 0.0 | 3.0 | 0.3 | 3.9 | 1.15 | 5.14 |
| 9 | 2 | 0.3 | 4.7 | 0.3 | 7.0 | 0.2 | 8.7 | 0.8 | 0.8 | 1.0 | 6.0 | 1.7 | 4.4 | 0.2 | 3.8 | 1.1 | 5.3 | 0.3 | 6.5 | 0.9 | 7.2 | 0.68 | 5.44 |
| 9 | 3 | 0.5 | 0.5 | 0.4 | 2.3 | 0.6 | 4.2 | 0.6 | 7.7 | 0.3 | 3.0 | 0.4 | 3.6 | 0.4 | 3.5 | 1.8 | 10.0 | 0.6 | 9.2 | 1.1 | 8.0 | 0.67 | 5.2 |
| 10 | 1 | 0.4 | 9.0 | 1.0 | 11.2 | 0.4 | 1.0 | 0.7 | 5.3 | 1.0 | 11.6 | 0.3 | 3.7 | 0.8 | 4.1 | 1.0 | 5.2 | 0.8 | 2.9 | 2.0 | 3.4 | 0.84 | 5.74 |
| 10 | 2 | 0.4 | 2.9 | 0.8 | 3.4 | 0.3 | 7.6 | 1.0 | 4.3 | 0.6 | 1.8 | 1.9 | 4.0 | 1.7 | 6.8 | 0.9 | 8.1 | 1.2 | 4.0 | 1.8 | 5.7 | 1.06 | 4.86 |
| 10 | 3 | 0.9 | 7.8 | 0.8 | 4.3 | 0.2 | 3.1 | 0.4 | 5.1 | 0.2 | 4.8 | 0.3 | 3.1 | 1.2 | 5.3 | 0.8 | 2.1 | 0.4 | 2.0 | 2.2 | 5.9 | 0.74 | 4.35 |
| 11 | 1 | 0.8 | 7.0 | 0.8 | 2.0 | 0.7 | 2.1 | 1.1 | 2.3 | 0.8 | 8.0 | 1.0 | 2.5 | 0.8 | 2.6 | 2.0 | 3.5 | 1.8 | 1.8 | 1.0 | 2.1 | 1.08 | 3.39 |
| 11 | 2 | 0.3 | 0.3 | 0.9 | 3.2 | 0.2 | 0.6 | 1.0 | 1.0 | 0.9 | 3.1 | 0.0 | 2.0 | 0.8 | 4.3 | 0.3 | 1.4 | 0.4 | 0.6 | 0.8 | 1.1 | 0.56 | 1.76 |
| 11 | 3 | 1.1 | 14.2 | 1.2 | 4.3 | 0.4 | 5.0 | 0.5 | 0.5 | 0.4 | 0.6 | 1.2 | 4.1 | 0.8 | 4.0 | 0.3 | 14.2 | 1.3 | 4.9 | 1.4 | 6.8 | 0.86 | 5.86 |
| 12 | 1 | 1.3 | 5.3 | 0.3 | 3.0 | 0.8 | 4.0 | 1.0 | 2.9 | 1.8 | 2.3 | 1.0 | 4.0 | 1.0 | 2.3 | 0.8 | 5.0 | 2.0 | 4.8 | 0.4 | 4.8 | 1.04 | 3.84 |
| 12 | 2 | 0.2 | 2.0 | 0.8 | 4.8 | 1.8 | 2.4 | 0.6 | 2.3 | 1.3 | 5.1 | 1.1 | 2.9 | 0.2 | 2.1 | 1.0 | 2.7 | 1.1 | 2.6 | 0.8 | 2.0 | 0.89 | 2.89 |
| 12 | 3 | 1.2 | 6.5 | 1.0 | 1.9 | 1.4 | 5.8 | 0.8 | 2.6 | 0.8 | 2.0 | 1.4 | 8.4 | 1.3 | 5.0 | 0.9 | 3.9 | 1.1 | 7.6 | 0.9 | 9.2 | 1.08 | 5.29 |
| 13 | 1 | 0.2 | 13.5 | 0.4 | 7.3 | 1.0 | 5.0 | 1.1 | 10.2 | 1.4 | 3.2 | 0.6 | 7.3 | 0.8 | 1.5 | 1.8 | 4.0 | 1.1 | 6.7 | 0.8 | 8.2 | 0.92 | 6.69 |
| 13 | 2 | 1.4 | 11.5 | 0.3 | 5.6 | 0.7 | 8.5 | 0.8 | 5.3 | 0.4 | 8.8 | 0.3 | 6.3 | 0.5 | 0.5 | 1.0 | 7.2 | 1.2 | 5.7 | 0.8 | 3.0 | 0.74 | 6.24 |
| 13 | 3 | 0.3 | 5.2 | 0.2 | 1.8 | 0.2 | 2.0 | 0.4 | 7.5 | 0.5 | 1.8 | 0.3 | 7.0 | 0.4 | 3.0 | 0.4 | 0.4 | 0.3 | 7.6 | 0.2 | 1.2 | 0.32 | 3.75 |
| 14 | 1 | 1.6 | 3.2 | 1.5 | 5.0 | 1.0 | 2.4 | 0.3 | 1.2 | 0.2 | 0.8 | 0.2 | 1.8 | 0.3 | 2.1 | 0.8 | 5.2 | 0.8 | 7.4 | 1.2 | 3.0 | 0.79 | 3.21 |
| 14 | 2 | 0.2 | 2.0 | 0.4 | 2.3 | 0.8 | 2.1 | 0.3 | 1.0 | 1.8 | 3.9 | 0.8 | 3.0 | 1.0 | 1.9 | 1.3 | 2.1 | 0.2 | 0.8 | 0.4 | 0.4 | 0.72 | 1.95 |
| 14 | 3 | 0.3 | 2.8 | 0.3 | 2.6 | 0.5 | 5.3 | 1.8 | 5.7 | 1.1 | 3.4 | 0.7 | 3.8 | 0.6 | 2.8 | 1.3 | 5.2 | 0.8 | 1.2 | 0.4 | 4.9 | 0.78 | 3.77 |
| 15 | 1 | 1.0 | 6.1 | 1.2 | 8.9 | 0.9 | 4.1 | 0.4 | 2.9 | 0.8 | 3.1 | 0.4 | 4.3 | 2.2 | 4.8 | 0.7 | 5.9 | 0.2 | 1.3 | 0.6 | 4.1 | 0.84 | 4.55 |
| 15 | 2 | 0.8 | 4.8 | 0.8 | 2.2 | 0.6 | 3.3 | 0.3 | 4.0 | 0.2 | 1.2 | 0.6 | 0.7 | 0.8 | 8.1 | 0.0 | 0.0 | | | | | 0.41 | 2.43 |
| 15 | 3 | 0.6 | 0.8 | 0.4 | 4.1 | 1.0 | 4.0 | 0.3 | 2.9 | 0.3 | 2.0 | 0.2 | 1.3 | 0.2 | 2.8 | 0.4 | 3.8 | 0.8 | 6.0 | 0.4 | 5.6 | 0.46 | 3.33 |